Biochar with Alternate Wetting and Drying Irrigation: A Potential Technique for Paddy Soil Management

Ahmad Numery Ashfaqul Haque 1,2, Md. Kamal Uddin 1,*, Muhammad Firdaus Sulaiman 1, Adibah Mohd Amin 1, Mahmud Hossain 3,*, Zakaria M. Solaiman 4 and Mehnaz Mosharrof 1

1 Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, Serdang 43400, Selangor, Malaysia; numerybau@gmail.com (A.N.A.H.); muhdfirdaus@upm.edu.my (M.F.S.); adibahamin@upm.edu.my (A.M.A.); mmd.mehnaz@gmail.com (M.M.)
2 Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh 2202, Bangladesh
3 Department of Soil Science, Faculty of Agriculture, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh; mahmud.ss@bau.edu.bd
4 UWA School of Agriculture and Environment, and the UWA Institute of Agriculture, The University of Western Australia, Perth, WA 6009, Australia; zakaria.solaiman@uwa.edu.au

* Correspondence: mkuddin07@gmail.com

Abstract: Over half of the world’s population depends on rice for its calorie supply, although it consumes the highest amount of water compared to other major crops. To minimize this excess water usage, alternate wetting and drying (AWD) irrigation practice is considered as an efficient technique in which soil intermittently dried during the growing period of rice by maintaining yield compared to a flooded system. Continuous AWD may result in poor soil health caused by carbon loss, nutrient depletion, cracking, and affecting soil physical properties. Due to being a potential organic amendment, biochar has a great scope to overcome these problems by improving soil’s physicochemical properties. Biochar is a carbon enriched highly porous material and characterized by several functional groups on its large surface area and full of nutrients. However, biochar’s implication for sustaining soil physicochemical and water retention properties in the AWD irrigation systems has not been widely discussed. This paper reviews the adverse impacts of AWD irrigation on soil structure and C, N depletion; the potential of biochar to mitigate this problem and recovering soil productivity; its influence on improving soil physical properties and moisture retention; and the scope of future study. This review opined that biochar efficiently retains nutrients and supplies as a slow-release fertilizer, which may restrict preferential nutrient loss through soil cracks under AWD. It also improves soil’s physical properties, slows cracking during drying cycles, and enhances water retention by storing moisture within its internal pores. However, long-term field studies are scarce; additionally, economic evaluation is required to confirm the extent of biochar impact.

Keywords: rice; biochar; intermittent irrigation; nutrient availability; soil physical properties; water retention

1. Introduction

Rice is one of the most widely grown cereals globally; it serves as the staple food for people mainly living in developing countries [1]. In 2017, rice covered over 160 million ha of land by producing approximately 748 million tons of yield worldwide [2]. However, rice plants consume a huge amount of water to complete their life cycle. They use almost 34 to 43% of irrigation water on the earth [3]. An estimation found that producing 1 kg of rice requires about 3000 to 5000 L of irrigation water, which is 2–3 times higher than other cereals such as maize and wheat [4]. Generally, above 75% of rice is produced under the continuous flooded irrigation system throughout its growing season and this irrigation system wastes a huge amount of water through seepage, percolation, and evaporation [5]. In this situation, farmers face challenges to produce rice with limited irrigation due to the
Many researchers reported that AWD could save up to 43% irrigation water without significant yield loss during panicle initiation and flowering to avoid water stress and economic yield loss [8]. In AWD irrigation system, water is allowed to evaporate before the next irrigation and when the water level reaches 150 mm (−15 to −20 kPa matric potential) below the soil surface, it is re-irrigated to a ponding water depth of 50 mm to monitor the water level below the soil surface employs a field water tube (Figure 1) [7]. In safe AWD, fields are kept flooded during panicle initiation and flowering to avoid water stress and economic yield loss [8]. Many researchers reported that AWD could save up to 43% irrigation water without significant yield loss [7,9], but few studies reported that AWD has economic yield loss [10]; Xu et al. [11] found that AWD irrigation causes about 16% yield loss of rice.

Figure 1. Alternate wetting and drying (AWD) irrigation of rice (Image collected from Riaz et al. [12]).

Regarding a water-saving AWD irrigation system, it has not been extensively adopted because of its potential yield loss [13]. These differences under the AWD irrigation system may be due to the variation in soil type, physicochemical properties, moisture retention capacity, etc. These problems may be due to AWD practice creating swelling and shrinking in clay portions that generate cracks [14]. This phenomenon increases the percolation rate due to cracks formation, which permits accelerated bypass flow [15]. Nutrients present in the soil solution from the topsoil move rapidly to the subsoil through the cracks [14], resulting in nutrients deficiency in the rhizosphere zone. Nutrient loss through leaching much higher in AWD compared to continuous flooding irrigation systems [16]. Furthermore, in the moisture stress condition of AWD plants uptake a reduced amount of nutrients compared to the constant flooding irrigation system [17]. These impediments may reduce the water-saving effectiveness of AWD irrigation systems. To mitigate this problem, there is a scope of soil enrichment by promising organic amendment; organic residue possesses restoration capacity of soil—it enhances structural stability, improves soil structure and aggregation, increases water-holding capacity, and modifies nutrient cycling [18].

Biochar is one of the most universally used organic amendments—carbon-rich porous material produced by the thermal decomposition of organic residue under limited oxygen conditions and comparatively at low temperature (below 700 °C) in a sealed container [19]. Enrichment of soil by biochar exerts favorable hydrological properties of soil for crop pro-
duction and improves soil structure, porosity, and erosion [20,21]. By applying biochar, soil enriched by organic matter results in increased carbon content and adds nutrients such as nitrogen, potassium, phosphorus, and magnesium [22–25]. Major et al. [26] observed that due to the addition of wood biochar leaching of $K^+$, $Ca^{2+}$, $Mg^{2+}$, and $NO_3^-$ decreased by 31, 14, 22, and 2%, respectively. Moreover, the addition of sewage sludge biochar in clay loam ultisol reduced the leaching of the nutrients, i.e., $NH_4^+$, $NO_3^-$, $PO_4^{3-}$ and $K^+$ by 35.9%, 9.7%, 23.7%, and 23.4%, respectively [27]. Biochar dramatically impacts the physical properties of soil, i.e., structure, porosity, aggregation, bulk density, and hydrological properties, such as water-holding capacity, infiltration, available water capacity, etc. [28–30]. The incorporation of biochar produced from crop residue provides an adequate amount of silicon (Si), and it also imports nutrients such as N, P, and K directly and increases their availability [31]. Moreover, Si enriched biochar increases photosynthetic activity. It mitigates biotic and abiotic stress and the addition of phytolithic biochar positively influences the available Si and other plant nutrients, stable organic carbon, and enhances soil fertility [32]. It also acts as slow-releasing fertilizer and supplies different essential nutrients to plants. These characters may improve the soil quality, which is deteriorated due to the AWD irrigation practices.

There are a few review articles on this topic. Hence, an advanced understanding necessitates the interaction of soil and biochar under AWD conditions to achieve sustainable rice production in the water-saving condition. This review summarizes (i) adverse effects of AWD on soil structure, carbon, and nitrogen depletion; (ii) types of biochar and their characteristics; (iii) potential of biochar to enhance soil fertility and mechanism of nutrient retention; (iv) influence of biochar on soil physical properties and water retention; and (v) identify the scopes of future study.

2. Adverse Effect of AWD on Paddy Soil Structure

Air and water flow and their soil availability are influenced by soil’s textural types, affecting nutrient and water uptake and overall plant growth. Generally, paddy soil is dominated by the huge extent of clay content (most extensive element of mineral soil) and contains very high specific surface area, resulting in the remarkable capacity to hold soil water and nutrients [33]. As reported by USDA, the soil consists of a minimum of 35% of clay particles, and it is termed clay-textured soil if the characteristics of clay particle dominated soil [34]. The formation of cracks in heavy clay soil is a physical phenomenon with extensive agricultural impacts. The soil’s shrinkage and swelling capacity are mainly driven by properties such as moisture regime and clay content that differ in space [35]. In AWD soil, it is periodically irrigated when the soil dries and reflooded to 5 cm and maintains flooded and non-flooded conditions [36] causes swelling and shrinkage and generates cracking in the surface of paddy soil [37] because water is discharged from the clay microstructures. Hydrological soil properties are extensively altered by cracking characteristics as broad and deep cracks transfer the water rapidly from surface to subsoil [38]. The increase in the presence and intensity of cracks can boost water’s percolation by allowing quicker and more comprehensive seepage of water [39]. This leaching of water to below root zone causes scarcity of moisture to the shallow-rooted plant species [40]; as a result, water productivity is decreased [36]. Furthermore, the increased evaporation rate observed from the soil consists of a greater extent of cracks in which cracks served as a secondary evaporation plate and reduced water use efficiency [41]. The soil cracking is susceptible to soil moisture regime and textural class, and it is a prerequisite to avoid soil cracking when rice is produced under irrigation deficit conditions in heavy clay soil [42].

3. Effect of AWD on Organic Carbon and Nitrogen Depletion

The water-saving irrigation approach of rice faces subsequent aerobic conditions in the soil, which may significantly alter biogeochemical activity, nutrient dynamics, greenhouse gas emissions, and rice production [43]. Livsey et al. [44] recently reported, in a meta-analysis, that water-saving irrigation declined 52.3% of $CH_4$ emission but raised $CO_2$ to 44.8% and increased soil to atmospheric carbon flux of 25% compared to continuous
flooding irrigation. AWD irrigation system soils are saturated intermittently after a certain drying period, which poses recurring aerobic soil conditions [45]. Compared to continuous flooding irrigation, AWD provides more oxidizing conditions in the soil. This phenomenon may stimulate the decomposition of plant residue and organic matter in the soil, especially in rice’s vegetative growth stage [46]. This instance may generate increased CO$_2$ emissions from the soil by decaying organic matter and declining organic matter status in soil [47]. In the dry period of AWD, aerobic condition prevails and takes place heterotrophic respiration in the soil; this leads to enhanced soil organic carbon (SOC) mineralization process [48], which likely transforms paddy soil from carbon sinks to sources [44]. There is a positive and linear relationship between precipitation and SOC [49]; flooded rice systems may accumulate higher SOC compared to periodically irrigated paddy fields.

A theoretical change proceeds in the physical condition of soil under the AWD system. The transformation between the aerobic and anaerobic environment in soil controls the microbial activity, including mineralization, nitrification, and denitrification, which affects N leaching and availability [38]. However, AWD-imposed intermittent aerobic and anaerobic environments in topsoil may alter NH$_3$ volatilization and N leaching from paddy soil [50]. N loss from paddy enhanced by nitrification and denitrification under AWD, reported by Dong et al. [5] and Pandey et al. [51], results in low N uptake by the plant. AWD causes increased production of N$_2$O from paddy soil, and it must be reduced because it’s a greenhouse gas and accounts for the detrimental effects on global warming [52].

During AWD at the drying stage, the soil shrinks and creates desiccated cracks on the topsoil that allow for preferential flow and loss of nutrients [33,38]. During this stage, nitrate content increased in the soil due to the enhanced nitrification rates, although rice roots need significantly higher energy to assimilate NO$_3$-N compared to NH$_4$-N [53]. Furthermore, nitrate leaching increased during the re-irrigation stage due to the abhorrent charge between NO$_3^-$ and negatively charged soil particles [54]. Frequently, other materials, such as dissolved organic matter (DOM) and nitrogen, consist of soil water leached concurrently [55]. However, it contains a relatively less amount of DOM but is a significant factor for soil organic matter (SOM) cycling [56,57]. Moreover, it serves as a transporter of organically bound nutrients [58], along with the source of energy and carbon for microbes in subsurface soil [59].

4. Characteristics and Types of Biochar

The carbon enriched organic biochar is produced by the heating of biomass in a sealed container where O$_2$ supplies very little or absent [60]. The presence of a much more substantial fraction of aromatic C and complex aromatic structures is the utmost conspicuous chemical characteristic of biochar, making it different from other organic matters used in soil [61]. There are three different forms of condensed aromatic structure present in biochars, i.e., (i) amorphous C (prevails at low pyrolysis temperature), (ii) turbostratic C (generated at a higher temperature), and (iii) graphite C [62,63]. For biochar production, a wide range of biomass is available from different waste sources. Among them are categorized into five classes, namely, agricultural waste, human and animal waste, woody biomass, industrial waste, and aquatic plants [64]. Recent studies reported that characteristics of biochar produced from biomass are significantly affected by the type of feedstocks used and temperature maintained during the pyrolysis [19]. Biomass pyrolyzed in two methods, namely, fast pyrolysis (>500 °C) and slow pyrolysis (≤500 °C): slow pyrolysis required more time to char and produced higher quantities of biochar compared to fast pyrolysis [65]. The variation in these thermal treatments results in a wide range of specific surface area, porosity, volatile matter, pH values, cation exchange capacity (CEC), carbon, and ash content [66]. Pyrolysis of biomass at higher temperature generates biochar with specific surface area, greater porosity, high pH inclusive of ash and carbon content, whereas less CEC and volatile matter content [66]. Figure 2 illustrates the plant, soil and biochar interactions.
required more time to char and produced higher quantities of biochar compared to fast pyrolysis [65]. The variation in these thermal treatments results in a wide range of specific surface area, porosity, volatile matter, pH values, cation exchange capacity (CEC), carbon, and ash content [66]. Pyrolysis of biomass at higher temperature generates biochar with specific surface area, greater porosity, high pH inclusive of ash and carbon content, whereas less CEC and volatile matter content [66]. Figure 2 illustrates the plant, soil and biochar interactions.

Figure 2. Systemic potential mechanism of biochar in soil and plant system (image collected from Jatav et al. [67]).

The primary sources of feedstock for biochar production come from agriculture (crop and animal residue), food processing wastes, and forestry, i.e., wood biomass [68]. The elemental composition and physicochemical properties of biomass are significantly different among several plant species. As in the same species, these characteristics are diversified due to plant parts, harvesting time, and growing conditions [19,69]. Several studies reported that the feedstock enriched by immense lignin and mineral contents produced a higher biochar quantity [70,71]. The chemical properties of biochar produced from different feedstocks are shown in Table 1.

Table 1. Chemical properties of biochars produced from different feedstocks (Li et al. [72]).

| Biochar Type             | %C  | %N  | C/N | %Ash | pH     | Total P (g kg⁻¹) | Total K (g kg⁻¹) |
|-------------------------|-----|-----|-----|------|--------|-----------------|-----------------|
| Rice straw biochar      | 55.7| 1.1 | 50.2| 28.1 | 9.88   | 3.05            | 53.08           |
| Peanut straw biochar    | 54.7| 1.8 | 31.3| 30.3 | 10.25  | 2.78            | 38.35           |
| Corn straw biochar      | 63.4| 2.7 | 23.5| 15.9 | 8.67   | 5.64            | 29.92           |
| Bamboo chips biochar    | 89  | 0.2 | 498.9| 2.7  | 9.5    | 0.81            | 10.81           |
| Pine chips biochar      | 76.5| 0.3 | 261.4| 2.5  | 8.14   | 0.39            | 1.03            |

Specific biochar may not comply with all soil types. Physicochemical properties of biochar regulate its utilization in soil [72]; therefore, an intentional application of biochar is necessary to select suitable feedstock and production conditions to produce the biochar with common characteristics.

5. Potential of Biochar to Influence Different Chemical Properties of Soil

In the previous section, we discussed the detrimental effect of AWD irrigation on soil’s physicochemical properties for rice production. In this regard, there is a scope of using biochar as an amendment in the AWD irrigation system due to its several ameliorating chemical properties as follows:
5.1. Role of Biochar on Soil Carbon Enhancement

The soil organic carbon acts as a sink and source of carbon. A small change of it significantly affects the atmospheric CO$_2$ concentration, thereby altering the global carbon cycle [73] and may cause global warming. A dynamic equilibrium of carbon input is a loss from soil termed as soil carbon balance, which is affected by changing climate and human interventions. A large quantity of SOC is oxidized and released into the atmosphere as CO$_2$ [74]. Several studies reported that soil moisture is the major dynamic factor in the carbon cycle process. Within a specific range of variation, it exhibited a significant correlation with the organic carbon transformation [75]. Yang et al. [74] reported that water-saving irrigation systems of rice reduce the organic carbon content of the soil. Intermittent drying and wetting causes loss of SOC also observed by Borken et al. [76] and Butterly et al. [77].

The application of plant residues can increase soil organic carbon. The rapid decomposition rate turnover of these organic residues occurs very fast, and thus, carbon added from the plant residue is discharged into the atmosphere quickly [78]. By converting these plant residues to biochar through pyrolysis, carbon could be stored for thousands of years due to the pyrolysis temperature converting C into a further stable and recalcitrant form [79], which ultimately improves soil health by enhancing soil fertility [80]. Thereby, biochar is treated as a C source and a sink of C in the soil [81]. Several researchers reported the inclusion of biochar to soil increased soil carbon status. Laird et al. [82] reported that under the same fertilization application of biochar increased the SOC content; in clay-textured soil, the addition of biochar increased the soil microbial biomass C [83]; El-Naggar et al. [84] found that addition of biochar into calcareous soil enhance carbon sequestration. The combined incorporation of biochar in water-saving irrigation practices enhances the SOC and its related factors [74]. Incorporation of biochar into soil showed more C mineralization because of the rapid discharge of a slight labile fraction of biochar. Still, the loss of indigenous soil organic matter did not compensate by applying biochar [85]. Previously researchers pointed out that the stable internal structure of biochar constrained the surface oxidation of SOC, enhanced SOC stability against microbial decomposition, and mineralization rate of SOC decreased through promoting the SOC content [86,87]. Details of the biochar effect on soil carbon presented in Table 2.
Table 2. Effect of biochar addition on soil carbon © enhancement of different types of soil (different letters in the same column indicating significant difference among the biochar treatment).

| Soil Type            | Experiment Type and Duration | Crop     | Biochar Material          | Pyrolysis Temperature (°C) | Biochar Rate/Treatment | Effect % Change References |
|----------------------|------------------------------|----------|---------------------------|----------------------------|------------------------|---------------------------|
| Sand                 | Incubation 6 months          | Rice     | Rice husk ~600            | 0.1                        | -                      | [29]                      |
| Sandy loam           | Pot 4 months                 | Rice     | Rice straw                | 0.5                        | 8                      | [74]                      |
| Hydromorphic paddy soil | Field 2 consecutive cycles    | Rice     | Wheat straw 350–550       | 0 t ha⁻¹                   | 16.8%                  | [88]                      |
| Entic Halpudept      | Field 2 consecutive cycles    | Rice     | Bamboo chips and Rice straw 600 | 10 t ha⁻¹                  | 27.2%                  |                            |
|                      |                              |          |                           | 20 t ha⁻¹                  | 55.2%                  |                            |
|                      |                              |          |                           | 40 t ha⁻¹                  |                        |                            |
| Clay loam            | Field 2 crop cycles          | Rice     | Bamboo biochar + urea     | 15.2b                      | 62.7%                  | [89]                      |
|                      |                              |          | Rice straw biochar + urea | 24.73a                     | 39.5%                  |                            |
|                      |                              |          | Control + urea (435 kg ha⁻¹) | 14.18b                    | −6.7%                  |                            |
|                      |                              |          | Bamboo biochar + urea     | 24.08a                     | 58.4%                  |                            |
|                      |                              |          | Rice straw biochar + urea | 20.89a                     | 37.4%                  |                            |
Table 2. Cont.

| Soil Type           | Experiment Type and Duration | Crop                | Biochar Material   | Pyrolysis Temperature (°C) | Biochar Rate/Treatment | Effect (SOC g kg⁻¹) | % Change | References |
|---------------------|-----------------------------|---------------------|--------------------|-----------------------------|------------------------|---------------------|----------|------------|
| Entic Halpudept     | Field 1 growth cycle        | Rice and Wheat      | Municipal biowaste | 450–550                     | 0 t ha⁻¹ 40 t ha⁻¹     | Rice                |          | [90]       |
|                     |                             |                     |                    |                             |                        | 26.8b 32.2a         |          |            |
|                     |                             |                     |                    |                             |                        | Wheat (SOC)         |          |            |
|                     |                             |                     |                    |                             |                        | 25.2b 29.9a         |          |            |
|                     |                             |                     |                    |                             |                        | Increased 21% (rice) |          |            |
|                     |                             |                     |                    |                             |                        | 19% (wheat)         |          |            |
| Anthraquic Gleysols (Clay) | Field, 2 year             | Rice                | Rice husk (RH)     | -                           | Control Control + fertilizer | RHB (4.13 kg m⁻²) |          | [91]       |
|                     |                             |                     |                    |                             |                        | 15.40b 14.90b       | -3.2%    |            |
|                     |                             |                     |                    |                             |                        | 28.30a 28.70a       | +83.7%   |            |
| China Entic Halpudept | Field 4 months             | Rice                | Wheat straw        | 350–550                     | i. Without N 0 t ha⁻¹ 10 t ha⁻¹ 40 t ha⁻¹ | i. With N 0 t ha⁻¹ 10 t ha⁻¹ 40 t ha⁻¹ |            | [92]       |
|                     |                             |                     |                    |                             |                        | 23.5b 23.2b         | +2%      |            |
|                     |                             |                     |                    |                             |                        | 25.9b 23.2b         | +45%     |            |
|                     |                             |                     |                    |                             |                        | 36.9a 36.0a         | +17%     |            |
|                     |                             |                     |                    |                             |                        | 27.1b 36.0a         | +55%     |            |
5.2. Biochar Impact on Major Nutrient (N, P, K) Availability in Soil

For sustainable soil fertility enhancement in the last decade, applying biochar in the agricultural field turns into a research hotspot [14,93]. Biochar incorporation reinforces soil fertility by two approaches—first, by the addition of nutrients to the soil, and second, by adsorption of nutrients from other sources [65].

Biochar incorporation efficiently helps sustain soil inorganic nitrogen content, influencing the nitrogen mineralization rate and plant growth [94,95]. Nitrogen mineralization, the transformation of organic N into two forms, i.e., NH$_4^+$ (ammonification process) and NO$_3^-$ (nitrification process), is the fundamental way of available N uptake by plants [96]. Due to biochar application, nitrogen transformation is highly influenced by soil type, feedstock used, and biochar application rate [97]. The addition of fresh biochar in soil, implying a priming effect, thereby promotes microbial activity and SOM decomposition [98]; usually, this incident increases the gross N mineralization [99,100]. Denitrifying bacteria promotes loss of available NO$_3^-$ by converting to NO$_2$, N$_2$O, and N$_2$ [96], but the addition of biochar affects soil porosity and increases water-holding capacity due to activity of denitrifiers, which is reduced in these conditions, and enhanced soil NO$_3^-$ content [101,102]. Biochar addition in the soil promotes nitrate-N in soil, mainly attributed to the enhanced conversion of NH$_4^+$ to NO$_3^-$ due to the following mechanism: (i) biochar adsorbs phenolic complex (constrain nitrification) concomitantly increase nitrification [103]; (ii) biochar increases the diversity of components involved in soil ammonium-oxidizing bacteria, thereby indirectly enhancing the catalytic oxidation of NH$_4^+$ to NO$_3^-$ [104]; (iii) biochar enhances the soil nitrification process by promoting the nitrifying bacteria activity [105].

A consecutive two-year experiment in a subtropical paddy soil by Zhang et al. [88] demonstrated that the addition of biochar at 40 tha$^{-1}$ significantly increased soil total N. In another study, it was found that the addition of rice straw and bamboo biochar increased total N from 11.7 to 14.9% under waterlogged paddy soil [89]. Incorporation of municipal biowaste biochar @ 40 t ha$^{-1}$ increased 7% total soil N for rice and wheat, also reported by Bian et al. [90], although total N content in biochar usually does not reflect the release of the total amount when added to the soil, and it is less available in contrast to those in the initial feedstock [78,106]. Knicker [107] documented that the low bioavailability of N in biochar, due to the pyrolysis process involved in biochar production, causes heterocyclic compounds such as pyridines, pyrrolys, and imidazoles (black N). Several studies reported that the application of biochar decreased nitrogen availability [106,108]. However, maybe the adsorption of NH$_4^+$ and NO$_3^-$ on the biochar surface makes it less available to soil solution because of enhanced cation/anion exchange capacity [99,109]. Furthermore, biochar application also reduces the N mineralization by the transformation of inorganic N to organic N by microbial uptake or amino acid production [99]; biochar with a high C:N ratio (>25:1) reduces the N mineralization and immobilize the available inorganic N [109].

Biochar provides a good source of P, due to the high volatilization temperature, i.e., >700 °C; the residual concentration of P is around 0.4% in the biochar produced in higher temperature [110]. Biochar addition affects P availability in soil by different mechanisms—biochar affects P precipitation by modifying soil pH and thereby P ionic bond with the cations such as Al$^{3+}$, Ca$^{2+}$, and Fe$^{3+}$, or by adsorption of organic molecules that act as metal ion chelates (complex protein, carbohydrates, and phenolic acids) observed by [111]. These organic molecules are effectively adsorbed by charged or hydrophobic biochar by forming a biochar–organic complex and eventually increasing the P availability and retention [112]. Furthermore, soil microbes play a significant role in the P availability, bacterial species *Pseudomonas aeruginosa* and *Bacillus subtilis* promote P solubilization from Ca$_3$(PO$_4$)$_2$ [113]. Biochar addition promotes the profuse growth of bacteria that produce P solubilizing compounds thereby enhancing P bioavailability [114]. Organic P mineralized by phosphatase enzyme activity from microbial interaction and transformed to inorganic P for plant uptake; biochar incorporation in the soil promotes phosphatase activity [115,116]. Biochar enhanced P use efficiency by increasing mycorrhizal colonization, as reported by Blackwell et al. [117].
Pyrolysis of biochar feedstocks causes volatilization of many nutrients, while large K reserved content and transformed into highly soluble K salts [118]. Biochar addition increased the available K in soil due to its high ash content and adsorbs K ion to reduce leaching loss [119,120]. Furthermore, biochar application promotes K-solubilizing bacteria’s growth, thereby enhancing the release of K from K-containing clay minerals and increasing the K uptake by crops [120]. Several K-solubilizing bacteria such as Bacillus edaphicus and Bacillus mucilaginous can dissolve K-containing minerals by releasing organic anions that may precisely solubilize potassium rock or chelated silicon ions to release K into soil solution [121]. Wang et al. [122] observed that rice husk and sawdust biochar significantly increased the exchangeable cations such as Ca, Mg, K, and Na ranging from 60 to 670%. Laghari et al. [23] pointed out that biochar incorporation in two deserts soil increased all the nutrients such as the total C (11% and 7%), total P (70% and 68%), and total K (37% and 42%), respectively. A study by Li et al. [72] with the application of straw and wood biochar in subtropical paddy soil and observed a significant variation in total N, P, and K influenced by biochar feedstock and application rate. Similar findings were also noted by Chen et al. [123]. Results of a meta-analysis concluded that biochar addition increased P and K content in plants compared to solely chemical fertilizer application due to enhancing their availability by decreasing leaching loss and liming effect on soil [124]. Details of the findings from the previous study of above-mentioned nutrients (N, P, and K) are presented in Table 3.
Table 3. Enrichment of soil nutrients (N, P, and K) by biochar incorporation from previous studies (different letters in the same column indicating significant difference among the biochar treatment).

| Soil Type                  | Experiment Type and Duration | Crop      | Biochar Material                  | Pyrolysis Temperature (°C) | Biochar Rate/Treatment | Effects | % Change | References |
|----------------------------|-------------------------------|-----------|-----------------------------------|---------------------------|------------------------|---------|----------|------------|
| Typic Sulfosaprists        | Glasshouse 4 months           | Rice      | Oil palm empty fruit bunch        | 300–400                   | 0 t ha⁻¹                | 0.28a   | -        | [22]       |
|                            |                               |           |                                   |                           | 10 t ha⁻¹               | 0.29a   | 3.6%     |            |
|                            |                               |           |                                   |                           | 20 t ha⁻¹               | 0.28a   | 0.0%     |            |
|                            |                               |           |                                   |                           | 40 t ha⁻¹               | 0.30a   | 7.1%     |            |
| China Entic Halpudept      | Field 2 consecutive cycles     | Rice      | Wheat straw                       | 350–550                   | 0 t ha⁻¹                | 1st cycle         |         |          |            |
|                            |                               |           |                                   |                           | 10 t ha⁻¹               | 2.07b   | +5.8%    | [88]       |
|                            |                               |           |                                   |                           | 20 t ha⁻¹               | 2.19b   | +1.9%    |            |
|                            |                               |           |                                   |                           | 40 t ha⁻¹               | 2.11b   | +22.7%   |            |
|                            |                               |           |                                   |                           | 1st cycle               | 2.54a   |          |            |
|                            |                               |           |                                   |                           | 2nd cycle               | 1.98b   | −1.5%    |            |
|                            |                               |           |                                   |                           |                        | 1.95b   | +9.1%    |            |
|                            |                               |           |                                   |                           |                        | 2.16ab  | +14.6%   |            |
|                            |                               |           |                                   |                           |                        | 2.27a   |          |            |
| Clay loam                  | Field 2 crop cycles           | Rice      | Bamboo chips and Rice straw       | 600                       | Control (No biochar and urea) | 2.13bc  | -        | [89]       |
|                            |                               |           |                                   |                           | Bamboo biochar (2.25 t ha⁻¹) | 2.32ab  | +8.9%    |            |
|                            |                               |           |                                   |                           | Rice straw biochar (2.25 t ha⁻¹) | 2.38a   | +11.7%   |            |
|                            |                               |           |                                   |                           | Control + urea (435 kg ha⁻¹) | 2.08c   | −2.3%    |            |
|                            |                               |           |                                   |                           | Bamboo biochar + urea    | 2.17abc | +1.9%    |            |
|                            |                               |           |                                   |                           | Rice straw biochar + urea| 2.39a   | +12.2%   |            |
| Anthraquic Gleysols (Clay) | Field, 2 year                 | Rice      | Rice husk                         | -                         | Control                 | 1.41b   | -        | [91]       |
|                            |                               |           |                                   |                           | Control + fertilizer    | 1.39b   | −1.42%   |            |
|                            |                               |           |                                   |                           | RHB (4.13 kg m⁻²)       | 1.64a   | +16.31%  |            |
|                            |                               |           |                                   |                           | RHB (4.13 kg m⁻²) +fertilizer | 1.63a   | +15.60%  |            |
|                            |                               |           |                                   |                           | Untreated rice husk     | 1.46b   | +3.55%   |            |
|                            |                               |           |                                   |                           | Untreated rice husk + fertilizer | 1.48b  | +4.96%   |            |
### Table 3. Cont.

| Soil Type         | Experiment Type and Duration | Crop          | Biochar Material      | Pyrolysis Temperature (°C) | Biochar Rate/Treatment | Effects | % Change | References |
|-------------------|------------------------------|---------------|-----------------------|----------------------------|------------------------|---------|----------|------------|
| Entisulfudult     | Field 4 months               | Rice          | Wheat straw           | 350–550                    | i. Without N           |         |          | [92]       |
|                   |                              |               |                       |                            | (TN g kg⁻¹)            |         |          |            |
|                   |                              |               |                       |                            | 0 t ha⁻¹                | 1.78d   | +19%     |            |
|                   |                              |               |                       |                            | 10 t ha⁻¹               | 2.12bcd | +39%     |            |
|                   |                              |               |                       |                            | 40 t ha⁻¹               | 2.48ab  |          |            |
|                   |                              |               |                       |                            | i. With N              |         |          |            |
|                   |                              |               |                       |                            | 0 t ha⁻¹                | 2.07cd  | +6%      |            |
|                   |                              |               |                       |                            | 10 t ha⁻¹               | 2.19abc | +23%     |            |
|                   |                              |               |                       |                            | 40 t ha⁻¹               | 2.54a   |          |            |
| Acidic soil       | Greenhouse 13 weeks          | Rice          | Sewage sludge         | 550                        | 0 g kg⁻¹                | 0.04    | +350%    | [125]      |
|                   |                              |               |                       |                            | 5 g kg⁻¹                | 0.18    | +550%    |            |
|                   |                              |               |                       |                            | 10 g kg⁻¹               | 0.26    |          |            |
| Sandy loam        | Incubation 60 days           | -             | Rice husk and Rice straw | 700                       | Rice husk biochar (RHB) |         |          | [123]      |
|                   |                              |               |                       |                            | (0, 5, 10, 20, 50 g kg⁻¹) | 0.04    | +16%     |            |
|                   |                              |               |                       |                            | Rice straw biochar (RSB) | 0.18    | +11%     |            |
|                   |                              |               |                       |                            | (0, 5, 10, 20, 50 g kg⁻¹) | 0.26    | +14%     |            |
| Silty loam        |                              | -             | Straw biochar (SB)     | 500                        |                        | Increased significantly with increment rate | +16%, +11% |            |
|                   |                              |               | Wood chip biochar (WCB) |                            |                        |         |          |            |
|                   |                              |               | Wastewater biochar (WWB) |                            |                        |         |          | [126]      |
| Vertisol Clay     | Incubation 180 days          | -             |                        |                            |                        | Increased significantly with increment rate | +16%, +11% |            |
|                   |                              |               |                        |                            |                        |         |          |            |
Table 3. Cont.

| Soil type                | Experiment type and duration | Crop       | Biochar material                        | Pyrolysis Temperature (°C) | Biochar rate/treatment | Effects | % Change | References |
|--------------------------|-----------------------------|------------|----------------------------------------|---------------------------|------------------------|---------|----------|------------|
| Typic Sulfosaprists      | Glasshouse 4 months         | Rice       | Oil palm empty fruit bunch             | 300–400                   | 0 t ha\(^{-1}\)        | 71.09ab | −5.2%    | [22]       |
|                          |                             |            |                                        |                           | 10 t ha\(^{-1}\)       | 67.36b  | +2.3%    |            |
|                          |                             |            |                                        |                           | 20 t ha\(^{-1}\)       | 72.71ab | +40.7%   |            |
|                          |                             |            |                                        |                           | 40 t ha\(^{-1}\)       | 100.01a |          |            |
| Dystroxerepts (Sand)     | Field 160 days              | Cucumber   | Poultry litter biochar (PLB)           | 450                       | PLB combinedly applied with compound poultry manure and N, P | All treatment combination increased significantly (\(p < 0.05\)) over control | Up to +71% | [24]       |
| Anthraquic Gleysols (Clay)| Field, 2 year               | Rice       | Rice husk                              | -                         | Control                | 13.30bc |          |            |
|                          |                             |            |                                        |                           | Control + fertilizer   | 15.00a  | +12.78%  | [91]       |
|                          |                             |            |                                        |                           | RHB (4.13 kg m\(^{-2}\)) | 14.70ab | +10.53%  |            |
|                          |                             |            |                                        |                           | RHB (4.13 kg m\(^{-2}\)) + fertilizer | 15.70a  | +18.05%  |            |
|                          |                             |            |                                        |                           | Untreated Rice husk    | 13.30bc | +0.00%   |            |
|                          |                             |            |                                        |                           | Untreated Rice husk + fertilizer | 15.00a  | +12.78%  |            |
| Sandy loam Silty loam    | Incubation 60 days          | Rice husk and Rice straw                   | 700                       | Rice husk biochar (RHB) (0, 5, 10, 20, 50 g kg\(^{-1}\)) | Increased with higher rate of both biochar in two types of soil. | Up to +171% | [123]      |
| Vertisol Clay            | Incubation 180 days         | Straw biochar (SB)                          | 500                       | 0 g kg\(^{-1}\)         | Increased significantly (\(p < 0.05\)) with increment rate | +79%, +15% and +153% by SB, WCB and WWB respectively | [126]       |
|                          |                             | Wood chip biochar (WCB)                     |                           | 20 g kg\(^{-1}\)        |                        |         |          |            |
|                          |                             | Wastewater biochar (WWB)                   |                           | 40 g kg\(^{-1}\)        |                        |         |          |            |
|                          |                             |                                        |                           | 60 g kg\(^{-1}\)        |                        |         |          |            |
| Dystroxerepts (Sand)     | Glasshouse 8 weeks          | Wheat     | Chicken manure and Wheat chaff         | 450                       | 0, 1, and 2% (w/w)     | Increased microbial biomass P | Up to +48% | [127]      |
**Table 3. Cont.**

| Location and Soil type | Experiment type and duration | Crop | Biochar material | Pyrolysis Temperature (°C) | Biochar rate/treatment | Effects % Change | References |
|------------------------|------------------------------|------|------------------|-----------------------------|------------------------|-----------------|-----------|
| Typic Sulfosaprists    | Glasshouse, 4 months        | Rice | Oil palm empty fruit bunch | 300–400                     | 0 t ha\(^{-1}\)          | 0.09c          | +44.4%    | [22]      |
|                        |                              |      |                   |                             | 10 t ha\(^{-1}\)         | 0.13bc         | +66.7%    |           |
|                        |                              |      |                   |                             | 20 t ha\(^{-1}\)         | 0.15ab         |           |           |
|                        |                              |      |                   |                             | 40 t ha\(^{-1}\)         | 0.19a          | +111.1%   |           |
| Dystroxerepts (Sand)   | Field, 160 days              | Cucumber | Poultry litter biochar (PLB) | 450                        | PLB combinedly applied with compound poultry manure and N, P | All treatment combination increased significantly (\(p < 0.05\)) over control | Up to +82% | [24]      |
| EnticHalpudept         | Field, 1 season              | Rice and Wheat | Municipal biowaste | 450–550                   | 0 t ha\(^{-1}\)          | (mg kg\(^{-1}\)) Rice 116b Wheat 106b | Increased 26% (rice) and 22% (wheat) | [90]      |
|                        |                              |      |                   |                             | 40 t ha\(^{-1}\)         | 148a           |           |           |
| Anthraquic Gleysols (Clay) | Field, 2 year            | Rice | Rice husk | -                           | Control                  | 1.59b          | -         | [91]      |
|                        |                              |      |                   |                             | Control + fertilizer     | 1.65ab         | +3.77%    |           |
|                        |                              |      |                   |                             | RHB (4.13 kg m\(^{-2}\)) | 1.70a          | +6.92%    |           |
|                        |                              |      |                   |                             | RHB (4.13 kg m\(^{-2}\)) + fertilizer | 1.68ab         | +5.66%    |           |
|                        |                              |      |                   |                             | Untreated rice husk      | 1.71a          | +7.55%    |           |
|                        |                              |      |                   |                             | Untreated rice husk + fertilizer | 1.70a          | +6.92%    |           |
| Sandy loam, Sand       | Field, 1 year               | Maize and Groundnut rotation | Maize cob | 350                        | 0%, 2.5%, 5% and 10%    | Significantly (\(p < 0.05\)) increased | 8 to 18 folds | [119]    |
| Tea garden soil        | Incubation, 60 days         | Rice husk | Rice husk | 550                        | (% w/w) (0, 0.5, 1, 2, 4) | Maximum increased by 4% rate | 6.7 folds | [122]    |
| Location and Soil type | Experiment type and duration | Crop      | Biochar material | Pyrolysis Temperature (°C) | Biochar rate/treatment | Effects | % Change | References |
|------------------------|-----------------------------|-----------|------------------|-----------------------------|------------------------|---------|----------|------------|
| Acidic soil            | Greenhouse 13 weeks         | Rice      | Sewage sludge    | 550                         | 0 g kg\(^{-1}\) (Control) 5 g kg\(^{-1}\) 10 g kg\(^{-1}\) | Increased 3% | +23%     | [125]      |
| Sandy loam             | Incubation 60 days          | -         | Rice husk and Rice straw | 700                         | Rice husk biochar (RHB) (0, 5, 10, 20, 50 g kg\(^{-1}\)) Rice straw biochar (RSB) (0, 5, 10, 20, 50 g kg\(^{-1}\)) | Biochar doses increased in sandy and siltysoil and RSB performed better over RHB | up to 14 times | [123]      |
| Silty loam             |                             |           |                  |                             |                        |         |          |            |
| Vertisol Clay          | Incubation 180 days         | -         | Straw biochar (SB) Wood chip biochar (WCB) Wastewater biochar (WWB) | 500                         | 0 g kg\(^{-1}\) 20 g kg\(^{-1}\) 40 g kg\(^{-1}\) 60 g kg\(^{-1}\) | Increased significantly \(p < 0.05\) with increment rate | 97%, 36% and 10% by SB, WCB and WWB respectively | [126]      |
| Clay loam              | Pot, 70 days                | Lentil    | Rice husk        | ~300 to ~500                | Rate: (% w/w) Control (0) 0.4 0.8 1.6 2.4 3.3 | (mg kg\(^{-1}\) 108.00f 121.33e 140.00d 176.67c 218.67b 256.00a | - 12% 30% 64% 102% | [128]      |
5.3. Capacity of Biochar to Retain Nutrients in Soil

Biochar directly absorbed plant nutrients from the crop, but within few soil interactions, some nutrients were slowly released into the soil, and thereby biochar enriched the nutrient source of soil for plant uptake [129]. Properties such as porous structure, large surface area, higher charge density, and polar and nonpolar sites in the surface of biochar enhance its potential to absorb nutrients and enrich the soil fertility and reduce leaching loss of nutrients [130]. Several studies found that biochar has great potential to absorb nutrients. Yao et al. [9] reported 3.7% of NO\textsubscript{3}\textsuperscript{−}, 15.7% of NH\textsubscript{4}\textsuperscript{+}, and 3.1% PO\textsubscript{4}\textsuperscript{3−} effectively absorbed by biochar. Thus, it is essential to understand the mechanisms of nutrient adsorption by biochar, for example, adsorption of NH\textsubscript{4}\textsuperscript{+} ion on biochar surfaces due to physical adsorption [8], negatively charged surfaces absorbed NH\textsubscript{4}\textsuperscript{+} [88], the formation of amine and amides by the reaction of NH\textsubscript{4}\textsuperscript{+} against acidic functional group [131], and cationic sites of biochar surface fixed NH\textsubscript{4}\textsuperscript{+} [132]. Details of biochar impact on cation exchange capacity of soil are mentioned in Table 4.

Generally, the following mechanisms are responsible for nutrient retention and reduced nutrient leaching capacity of biochar: (i) biochar has unique surface chemistry, i.e., presence of acidic functional group on biochar surface formed during oxidation procedure prompt the nutrient retention by cation exchange (Figure 3); thus, most of the cations, e.g., K, Na, Ca, and Mg are retained on the biochar surface [96]. Enhanced cation exchange capacity is a special characteristic of biochar surface chemistry responsible for increased nutrient retention [133]; moreover, it has anion exchange sites that help to retain anions (NO\textsubscript{3}\textsuperscript{−}, PO\textsubscript{4}\textsuperscript{3−}) and reduce their leaching loss; (ii) by influencing physicochemical properties, biochar modifies nutrient retention of soil; typically, biochar shows high pH value. In many cases, it is applied as a liming agent, and therefore, it can indirectly change the nutrient solubility in soil solution [134]. Biochar increased nutrient retention by affecting the soil’s physical properties such as bulk density, porosity, aggregate stability, and moisture retention [126]; and (iii) biochar has a great potential to modify the abundance, distribution, and activity of soil microbial communities [135,136]. Biochar shows pore spaces within its structure, which serve as a habitat for soil microbes [135]. Dissolved organic carbon and nutrients released from biochar surface are liable for microbial growth and cause the modification of nutrient dynamics and thereby nutrient retention [99].

![Figure 3. Schematic diagram representing how biochar improves the retention of nutrients and increases their availability in soils (Reprinted from Chemosphere, 227, Purakayastha, T.J. et al., A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: Pathways to climate change mitigation and global food security, 345–365, Copyright (2019), with permission from Elsevier. [137]).](image-url)
Table 4. Effect of biochar on cation exchange capacity (CEC) of soil (different letters in the same column indicating significant difference among the biochar treatment).

| Soil Type      | Experiment Type and Duration | Crop    | Biochar Material                        | Pyrolysis Temperature (°C) | Biochar Rate/Treatment | Effects                              | % Change | References |
|----------------|-----------------------------|---------|----------------------------------------|-----------------------------|------------------------|--------------------------------------|----------|------------|
| Typic Sulfosaprist | Glasshouse 4 months         | Rice    | Oil palm empty fruit bunch             | 300–400                     | 0 t ha⁻¹               | 24.26b                              | +1.8%    | [22]       |
|                |                              |         |                                        |                             | 10 t ha⁻¹              | 24.70ab                             | +3.6%    |            |
|                |                              |         |                                        |                             | 20 t ha⁻¹              | 25.13ab                             | +7.6%    |            |
|                |                              |         |                                        |                             | 40 t ha⁻¹              | 26.10a                              |          |            |
| Sandy          | Incubation 6 months         | - Rice husk | (%) w/w                              | ~600                        | 0          | Increased significantly (p < 0.05) | +17%     | [29]       |
| Sandy loam     | Incubation 60 days          | -       | Rice husk and Rice straw              | 700                         | Rice husk biochar (RHB) | Increased up to 40%                    |          | [123]      |
|                |                              |         |                                        |                             | (0, 5, 10, 20, 50 g kg⁻¹) | Higher dose of biochar increased CEC value in both soils |          |            |
|                |                              |         |                                        |                             | Rice straw biochar (RSB)| | | | | |
|                |                              |         |                                        |                             | (0, 5, 10, 20, 50 g kg⁻¹) | | | | |
|                |                              |         |                                        |                             |                        | | | | |
| China Ultisol  | Incubation 11 days          | -       | Rice straw                            | 250                         | (% w/w)               | Significantly (p < 0.05) increased          | +4–17%  | [138]      |
|                |                              |         |                                        |                             | 0% (Control)           | | | | |
|                |                              |         |                                        |                             | 1%                     | | | | |
| Loam           | Greenhouse 42 days          | Lettuce | Walnut shell                          | 900                         | 10 metric t ha⁻¹      | Significantly (p < 0.05) increased        | +64%    | [139]      |
6. Impact of Biochar on Physical and Hydrological Properties of Soil

Physical health of the soil is defined as the soil’s capacity to provide plants’ needs for aeration, moisture, and strength, which protect and reclaim the soil from the processes that might abate that capacity [140]. Biochar is an organic amendment characterized by high porosity, and application of this material into soil explicitly adds new pores and promotes the soil’s physical properties including porosity, density, pore size distribution, water retention, and moisture content [141]. The influence of biochar in the following physical and hydrological properties of soil are discussed below from previous research findings. It is considered that the addition of the biochar improves the physical health of the soil that may be diminished by the AWD irrigation system of rice.

6.1. Bulk Density

The bulk density of soil indicates its compactness and ability of plant roots to enter into the soil. It affects the soil’s physical properties such as porosity, available plant water, water-holding capacity, and nutrient availability, and microbial processes in the soil, directly affecting soil productivity [142]. Many researchers reported that applying biochar in soil significantly influenced the soil’s bulk density (Table 5). Głąb et al. [28] reported that biochar’s addition decreased the soil’s bulk density, and maximum effect was observed when soil treated with 4% biochar reduced the bulk density upto 35%. The previous study observed that the degree of bulk density changes by biochar addition was significantly affected by the soil texture [142]. Fine-textured soil (clay) is less affected by biochar addition compared to coarse-textured (sandy) soil, in terms of the degree of changes in bulk density by biochar incorporation [28], but medium and fine-textured soil exhibited insignificant effects in some treatments [143]. Haefele et al. [91] reported that decreased bulk density was observed at the rainfed upland and irrigated lowland but did not affect the rainfed lowland soil due to biochar application. Biochar is characterized by porous, light material with very low density. Thus, the bulk density of soil decreased due to the addition of biochar [91].

6.2. Soil Porosity

The structure of soil pores includes the shape and size of pores, which extensively affects the moisture retention and gaseous exchange in the soil [144]. Soil properties such as saturated hydraulic conductivity are positively affected by the variation of soil porosity [145,146]. A favorable soil generates a suitable habitat for soil microbes and supports root growth, which consecutively enhances soil productivity [147]. An agricultural soil pore structure evolved from some self-organizing transformation of the soil and different management practices such as tillage and organic residual management [144]. Organic amendment such as the application of increased rate biochar correspondingly increased soil porosity, which eventually boosts soil productivity by controlling soil’s hydraulic properties [142]. Many studies reported that soil pore structure characteristics potentially changed by applying highly porous featured biochar (Table 6). The following possible mechanism of biochar function soil involved in the increase of soil porosity [148]: (i) highly porous biochar introduce additional pores, (ii) building packing or pores from the alteration of the soil pore system, and (iii) improvement of aggregate stability. Nevertheless, Verheijen et al. [141] reported that the outcome of these mechanisms might differ due to the variation in the combinations of soil, climate, and management practices.
| Soil Type      | Experiment Type and Duration | Crop                          | Biochar Material            | Pyrolysis Temperature (°C) | Biochar Rate | Effect | % Change | References |
|---------------|------------------------------|-------------------------------|------------------------------|----------------------------|--------------|--------|----------|------------|
| Loamy sand    | Incubation 4 months          | -                             | Winter wheat and Miscanthus  | 300                        | 0.5          | 1.59a  | -11%     | [28]       |
|               |                              |                               |                              |                            | 1.0           | 1.54b  | -14%     |            |
|               |                              |                               |                              |                            | 2.0           | 1.46c  | -19%     |            |
|               |                              |                               |                              |                            | 4.0           | 1.33d  | -26%     |            |
| Sand          | Incubation 6 months          | -                             | Rice husk                    | ~600                       | 0.1          | 1.48a  | -6       | [29]       |
|               |                              |                               |                              |                            | 0.5           | 1.39b  | -11      |            |
|               |                              |                               |                              |                            | 1.0           | 1.32c  | -14      |            |
|               |                              |                               |                              |                            | Control (0)   | 1.27e  | -7       |            |
|               |                              |                               |                              |                            | 0.1           | 1.41b  | -9       |            |
|               |                              |                               |                              |                            | 0.5           | 1.31cd | -12      |            |
| Sandy loam    |                              | -                             | Wood                         | -                          | 1.0           | 1.24e  | -12      |            |
| Mesic typic   | Incubation 500 days          | -                             | Wood                         | i. Biochar (0, 5, 10, 20 g kg\(^{-1}\)) without manure | Non significant | - |          | [82]       |
| Hapludolls    |                              |                               |                              | ii. Biochar (0, 5, 10, 20 g kg\(^{-1}\)) manure |              |        |          |            |
| Entic Halpudept | Field 2 consecutive cycles    | Rice                          | Wheat straw                  | 350–550                    | 0 t ha\(^{-1}\) | 0.99   | -3.0%    | [88]       |
|               |                              |                               |                              |                            | 10 t ha\(^{-1}\) | 0.96   | -8.1%    |            |
|               |                              |                               |                              |                            | 20 t ha\(^{-1}\) | 0.91   | -10.1%   |            |
|               |                              |                               |                              |                            | 40 t ha\(^{-1}\) | 0.89   | -        |            |
|               |                              |                               |                              |                            | 1st cycle     |        |          |            |
|               |                              |                               |                              |                            | 0 t ha\(^{-1}\) | 0.94   | -3.2%    |            |
|               |                              |                               |                              |                            | 10 t ha\(^{-1}\) | 0.91   | -8.5%    |            |
|               |                              |                               |                              |                            | 20 t ha\(^{-1}\) | 0.86   | -6.4%    |            |
|               |                              |                               |                              |                            | 40 t ha\(^{-1}\) | 0.88   |          |            |
|               |                              |                               |                              |                            | 2nd cycle     |        |          |            |

**Table 5.** Effect of biochar on bulk density (g/cc) of different types of soil (different letters in the same column indicating significant difference among the biochar treatment).
Table 5. Cont.

| Soil Type            | Experiment Type and Duration | Crop       | Biochar Material | Pyrolysis Temperature (°C) | Biochar Rate | Effect | % Change | References |
|----------------------|------------------------------|------------|------------------|---------------------------|--------------|--------|----------|------------|
| Entic Hapludult      | Field 4 months               | Rice       | Wheat straw      | 350–550                   |              |        |          |            |
|                      |                              |            |                  | i. Without N             |              |        |          |            |
|                      |                              |            |                  | 0 t ha⁻¹                 | 1.01a        |        | −3%      | [92]       |
|                      |                              |            |                  | 10 t ha⁻¹                | 0.98ab       |        | −12%     |            |
|                      |                              |            |                  | 40 t ha⁻¹                | 0.89c        |        | −9%      |            |
|                      |                              |            |                  | ii. With N               |              |        |          |            |
|                      |                              |            |                  | 0 t ha⁻¹                 | 0.99ab       |        | −3%      |            |
|                      |                              |            |                  | 10 t ha⁻¹                | 0.96ab       |        | −10%     |            |
|                      |                              |            |                  | 40 t ha⁻¹                | 0.89c        |        |          |            |
| Sandy                | Field 2 year                 | Maize      | Birch wood       | 500                       | 0 t ha⁻¹     | Decreased | Up to −16% | [144] |
|                      |                              |            |                  | 20 t ha⁻¹                | 0.99ab       |        | −16%     |            |
|                      |                              |            |                  | 40 t ha⁻¹                | 0.96ab       |        | −10%     |            |
|                      |                              |            |                  | 100 t ha⁻¹               | 0.89c        |        |          |            |
| Loam                | Field 4 year                 | Peanut shell|                  | 350–500                   | 0 Mg ha⁻¹    | 1.36a    | −4%      | [149] |
|                      |                              |            |                  | 28 Mg ha⁻¹               | 1.31b        |        |          |            |

Table 6. Changes in soil porosity by biochar incorporation (different letters in the same column indicating significant difference among the biochar treatment).

| Soil Type            | Experiment Type and Duration | Crop       | Biochar Material | Pyrolysis Temperature (°C) | Biochar Rate | Effect | Total porosity (cm² cm⁻³) | % Change | References |
|----------------------|------------------------------|------------|------------------|---------------------------|--------------|--------|---------------------------|----------|------------|
|                      |                              |            |                  | Rate: (w/w)               |              |        |                           |          |            |
|                      |                              |            |                  | 0%                        | 0.322        |        |                           | -        | [28]       |
|                      |                              |            |                  | 0.5%                      | 0.395d       | +23    |                           |          |            |
|                      |                              |            |                  | 1%                        | 0.414c       | +29    |                           |          |            |
|                      |                              |            |                  | 2%                        | 0.442b       | +37    |                           |          |            |
|                      |                              |            |                  | 4%                        | 0.489a       | +52    |                           |          |            |
Table 6. Cont.

| Soil Type     | Experiment Type and Duration | Crop            | Biochar Material | Pyrolysis Temperature ($^\circ$C) | Biochar Rate | Effect                                      | % Change | References |
|---------------|------------------------------|-----------------|------------------|-----------------------------------|--------------|---------------------------------------------|----------|------------|
| Sand          | Incubation 6 months          | Rice husk       | 600              | Control (0)                        | 0.1          | Increased significantly ($p < 0.05$) with increment rate | +8%      | [29]       |
| Sandy loam    |                              |                 |                  |                                    | 0.5          | +14%                                        | +19%     |            |
|               |                              |                 |                  |                                    | 1.0          | +19%                                        |          |            |
| Vertisol (Clay) | Incubation 180 days         | Fruit tree      | 500              | 0 g kg$^{-1}$, 20 g kg$^{-1}$, 40 g kg$^{-1}$, 60 g kg$^{-1}$ | Increased significantly ($p < 0.05$) with increment rate | +13%     | [126]      |
| Vertisol (Clay) | Column study 2.5 years      | Maize           | 500              | 0% 1% 3%                           | Increased significantly ($p < 0.05$) | +13%     | [143]      |
| Sandy         | Field 2 year                 | Birch wood      | 500              | 0 t ha$^{-1}$, 20 t ha$^{-1}$, 40 t ha$^{-1}$, 100 t ha$^{-1}$ | Increased Upto+14% | +37% | [144]   |
6.3. Soil Aggregate Stability

Soil aggregate stability is considered an important soil physical property that indicates soil quality [150]; Hortensius and Welling [151] included it as the parameter of soil quality in the international standard. Aggregate stability is a major factor build up the soil’s capacity against mechanical stress such as water erosion, surface runoff, and precipitation effect [152]. The disintegration of the soil aggregates into fine particles makes the soil vulnerable to water and wind erosion. The sedimentation of these particles clogs the soil pores by forming surface crust [153]. Soil aggregates conserve and protect organic matter and enhance soil structure and porosity, root growth, penetration, plant available water, drought resistance, and microbial activity [142]. Improvement of soil aggregates stability obtained by adding organic amendments has been reported by several researchers [21,65,150]. A quality organic amendment application of biochar has great potential to improve the soil aggregate stability (Table 7). Verheijen et al. [141] proposed that the inclusion of biochar enhances soil porosity through the improvement of aggregate stability. Jien and Wang [20] proclaimed that, in an incubation study, application of biochar induces the formation of aggregates that may cause short-term changes in pore size distribution. However, several researchers observed no significant differences in the soil aggregate stability due to the application of biochar [138,154].

6.4. Soil Crack Formation

The presence of a high quantity of clay is a common feature of paddy soil. It is the most crucial mineral soil component because of its large specific area and its capacity to bind nutrients and water [42]. With intermittent drying and wetting conditions, clay minerals expand and become sticky and muddy by absorbing moisture as they get wet; conversely, the formation of desiccated cracks that appeared on the soil surface shrink during the drying period [155]. Soil cracks are crucial from a different point of view, and they allow increased water infiltration also transport the nutrients to the subsoil [156]. For instance, plant roots may physically be damaged by these cracks. It also results in surface moisture loss and nutritional stress to plants by leaching loss of nutrients from the rhizosphere zone, ultimately restricting the soil for crop production [157]. Under the circumstances, it is crucial to mitigate this problem for sustainable rice production. Organic amendments such as crop residues and biochar can be used to recover the cracking, shrinking, and other poor physical properties of heavy clay soils [158]. The previous study of biochar impact on soil cracking is shown in Table 8. The possible mechanism involved in reducing crack formation in heavy clay soil may be caused by the carbon from the organic material interacting with soil minerals alter bond strength and surface tension characteristics of the soils, ultimately decreasing the shrink–swell potential [158].
Table 7. Soil aggregate stability of different types of soil influenced by biochar application.

| Soil Type                   | Experiment Type and Duration | Crop                  | Biochar Material                                  | Pyrolysis Temperature (°C) | Biochar Rate       | Effect                        | % Change         | References  |
|-----------------------------|------------------------------|-----------------------|---------------------------------------------------|----------------------------|--------------------|-------------------------------|------------------|-------------|
| Sand, Sandy loam, loamy sand| Field 1 year                 | Maize and Soybean     | Corn cob and rice husk                            | 300–350                    | 0–4%               | Significantly increased (p > 0.05) | +7 to 20%        | [21]        |
| Vertisol Clay               | Incubation 180 days          | -                     | Straw biochar (SB)                                | 500                        | 0 g kg⁻¹           | Increased significantly (p < 0.05) with increment rate | 21%, 84% and 140% by SB, WCB and WWB | [126]        |
| China Ultisol               | Incubation 11 days           | -                     | Rice straw                                        | 250–350                    | 0% (Control)       | Non significant               | -                | [138]       |
| Sandy loam                  | Field 1 year                 | Maize                 | Corn cob                                          | 360                        | 0, 4.5, 9 t ha⁻¹   | Non significant               | -                | [154]       |
| Alfisol (Silt loam)         | Incubation 295 days          | -                     | Corn stover                                       | Control 350                | Control 7.18 t C ha⁻¹ | Increased                    | >+17%            | [159]       |
| Andisol (Silt loam)         | -                            | Control 550           | Control 7.18 t C ha⁻¹                              | Increased                  | +7–15%              |                               |                  |             |
| Sandy loam                  | Incubation 11 months         | -                     | Pine sawdust                                      | 0, 4, 8, 16 (g kg⁻¹)       | NS                 |                               |                  | [160]       |
Table 8. Impact of biochar on recovering cracking parameters of different types of soil.

| Soil Type          | Experiment Type and Duration | Crop                  | Biochar Material                           | Pyrolysis Temperature (°C) | Biochar Rate | Effect                                                                 | % Change                                         | References |
|--------------------|-----------------------------|-----------------------|--------------------------------------------|----------------------------|--------------|----------------------------------------------------------------------|--------------------------------------------------|------------|
| Vertisol (Silty clay) | Not available               | -                     | Mixed Corn straw and Peanut shell          | 450                        | 0 g kg\(^{-1}\) | Decreased cracking area density with increasing biochar rates       | 33.6%, 52.1% for 50, 100 and 150 g kg\(^{-1}\) respectively | [93]       |
| Inceptisol Clay    | Incubation 280 days         | -                     | Rice husk                                 | 450                        | (w/w)        | Crack area density (%)                                               | [156]                                   |
|                    |                             |                       | Sugarcane bagasse                         |                            | 0%           | 12.68a                                                               |                                                  |
|                    |                             |                       |                                            |                            | 2%           | 8.87b                                                                | -30%                                             |
|                    |                             |                       |                                            |                            | 5%           | 6.42bc                                                               | -49%                                             |
|                    |                             |                       |                                            |                            | 10%          | 4.84c                                                                | -62%                                             |
|                    |                             |                       |                                            |                            | 0%           | 12.68a                                                               |                                                  |
|                    |                             |                       |                                            |                            | 2%           | 9.00b                                                                | -29%                                             |
|                    |                             |                       |                                            |                            | 5%           | 4.79c                                                                | -62%                                             |
|                    |                             |                       |                                            |                            | 10%          | 3.82c                                                                | -70%                                             |
| Vertisol Clay      | Incubation 180 days         | -                     | Straw biochar (SB) Wood chip biochar (WCB) | 500                        | 0 g kg\(^{-1}\) | All biochars reduced surface crack formation                         | 60 g kg\(^{-1}\) of SB, WCB and WWB             | [158]       |
|                    |                             |                       | Wastewater biochar (WWB)                  |                            | 20 g kg\(^{-1}\) |                                                                        | decreased 14, 17, 19% surface area cracking density respectively |
|                    |                             |                       |                                            |                            | 40 g kg\(^{-1}\) |                                                                        |                                                  |
|                    |                             |                       |                                            |                            | 60 g kg\(^{-1}\) |                                                                        |                                                  |
| Pukou (Clay)       | Not available               | -                     | Wood                                      | 500                        | 0, 0.5, 2, 4 and 6% (w/w)                                            | Reduced cracking ratio and number                | 16.85 and 32.26% respectively                   | [161]       |
6.5. Soil Water Retention Properties

The soil’s hydrological properties such as water-storage capacity and water movement within the soil are the most important for plant nutrient supply and productivity [162]. Biochar can change soil hydrology and consequently modify the water storage in soils [143]. Biochar interacts with water and builds a complex network employing surface-active chemicals and pores in the biochar particles [163]. Generally, the plant absorbs 0.1% to 10% silicon (Si) of dry shoot weight [164]. This plant-derived Si produces silica hydrogels by interacting with water molecules [165]. Accordingly, applying biochar originated from Si enriched raw materials may exhibit the same silica hydrogel or silica gel formation trend, which physically attracts soil water by reacting with water molecules [166] or store moisture through its internal pores [167]. Considering that, enhancing soil moisture-storage Si content of biochar is deemed to be an important characteristic.

Biochar can regulate soil water retention by modifying different physical properties of the soil such as by reducing bulk density [28], enhancing soil aggregation [159], changing pore size distribution, and improving soil porosity [21], and expanding the surface area of soil, i.e., soil surface area, exclusively in sandy soil [82]. Several studies indicated that the water-holding capacity of the soil was efficiently increased by biochar application and effectively suppressed soil crack formations [93,161,168]. Głab et al. [28] reported that the addition of 4% (wt/wt) biochar enhances soil available water content upto 128%. The moisture content of sandy loam and silty loam increased by rice husk and rice straw biochar incorporation [123]. Sun and Liu [126] observed that, depending on the application rate of straw, biochar increased the water content up to 18.4%, and woodchips biochar enhanced water-holding capacity upto 6.8% compared to control in a Vertisol clay soil. In clay soil, an increase of available water capacity with an increment rate of biochar reported by Kameyama et al. [169]; further addition of biochar increased gravimetric water content in clay-textured paddy soil, also reported by Haque et al. [170]. In some studies, there were no significant changes in soil water storage due to biochar application, presented in Table 9 [128,134].

6.6. Hydraulic Conductivity of the Soil

Hydraulic conductivity of soil indicates the ability of the soil to transport water [171]. Blanco-Canqui [172] mentioned that biochar impacts differently for a specific textural class; consecutively, biochar enhances the saturated hydraulic conductivity in the fine-textured soils, whereas it is reduced in coarse-textured soils. Similar findings were also reported by [23,29,173]. Generally, sandy soils are characterized by high hydraulic conductivity and less nutrient and water-holding capacity, resulting in less soil productivity [174]. The addition of biochar in sandy soil increased interpore and pore throat size and enhanced the tortuosity, consecutively increasing water retention and decreasing saturated hydraulic conductivity [173,175]. Therefore, rice cultivation in sandy soil becomes more important in terms of biochar incorporation for improved water use efficiency. The various studies suggested no significant changes in saturated hydraulic conductivity due to biochar addition in the soil [82,149,176]. Moreover, less attention has been paid to the influence of biochar on the hydrological soil properties of clay soil. The laboratory experiments found that the addition of biochar significantly increased saturated hydraulic conductivity in clay soil [20,30,173]. Application of biochar may increase hydraulic conductivity of clay soil but do not enhance loss of water through infiltration. Details of biochar’s impact on hydraulic conductivity of different types of soil are mentioned in Table 10.
Table 9. Soil moisture retention properties influenced by biochar application.

| Soil Type       | Experiment Type and Duration | Crop                  | Biochar Material                        | Pyrolysis Temperature (°C) | Biochar Rate/Treatment | Effect % Change References |
|-----------------|------------------------------|-----------------------|-----------------------------------------|-----------------------------|------------------------|---------------------------|
| Clay loam       | Field 2 crop cycles          | Rice                  | Bamboo chips and Rice straw             | 600                         | Control (No biochar and urea) 0.33 Bamboo biochar (2.25 t ha\(^{-1}\)) 0.34 Rice straw biochar (2.25 t ha\(^{-1}\)) 0.38 Control + urea (435 kg ha\(^{-1}\)) 0.35 Bamboo biochar + urea 0.36 Rice straw biochar + urea 0.38 | +3.0% [89] +15.2% +6.1% +9.1% +15.2% |
| Vertisol (Silty clay) | Not available                | Mixed Corn straw and Peanut shell | 450 (0, 50, 100, 150) g kg\(^{-1}\) | Increased gravimetric water content - [93] |
| Vertisol Clay   | Incubation 180 days          | -                     | Straw biochar (SB) Wood chip biochar (WCB) Wastewater biochar (WWB) | 500                         | 0 g kg\(^{-1}\) 20 g kg\(^{-1}\) 40 g kg\(^{-1}\) 60 g kg\(^{-1}\) | Increased significantly \((p < 0.05)\) with increment rate for straw biochar 1.4%, 6.1% and 18.4% respectively [126] |
| Vertisol (Clay) | Column study 2.5 years       | -                     | Fruit trees                             | 500                         | 0% 1% 3% | Increased significantly \((p < 0.05)\) at maximum biochar dose - [143] |
| Alisol (Silt loam) | Incubation 295 days          | -                     | Corn stover                            | Control 350 550 Control 7.18 t C ha\(^{-1}\) | Increased plant available water - [159] |
| Andisol (Silt loam) | Control 350 550              | -                     | Corn stover                            | Control 7.18 t C ha\(^{-1}\) | Increased plant available water - [159] |
| Sandy loam      | Pot 4 months                 | Barley                | Pine wood Wheat straw                  | 1200 750                    | 0 and 1% | Increased AWC 17 to 42% [162] |
| Loamy sand      | Column study 3 months        | -                     | Water hyacinth                         | 350–400                     | 0, 2, 5 and 10% \((w/w)\) | Increased soil moisture with increasing soil biochar content - [168] |
| Clay            | Laboratory 180 days          | -                     | Sugarcane                              | 400–800                     | 0, 1, 3, 5, 10% \((w/w)\) | Increased AWC with increment biochar rate greater than 3% ~60% [169] |
Table 10. Impact of biochar on saturated hydraulic conductivity of different types of soil.

| Soil Type          | Experiment Type and Duration | Crop | Biochar Material | Pyrolysis Temperature (°C) | Biochar Rate (%) w/w | Effect | % Change | References |
|--------------------|-------------------------------|------|------------------|-----------------------------|-----------------------|--------|----------|------------|
| Sand               | Incubation 6 months           | -    | Rice husk        | ~600                        | Control (0) 0.1 0.5 1.0 | Decreased significantly (p < 0.05) | -54      | [29]       |
| Sandy loam         |                               |      |                  |                             | 0% 5% 20%             | 1.2 × 10⁻⁹ m s⁻¹ 2.1 × 10⁻⁹ m s⁻¹ 1.3 × 10⁻⁹ m s⁻¹ | +75%     |            |
| Kaolin clay        | Column study                  | -    | Peanut shell     | 500                         | 0% 5% 20%             | Control 7.18 t C ha⁻¹ | Increased | 139%  [159]|
| Alfisol (Silt loam)| Incubation 295 days           | -    | Corn stover      | Control 350 550             | Control 7.18 t C ha⁻¹ | Increased | 139%     | [159]      |
| Andisol (Silt loam)|                               |      |                  |                             | Control 7.18 t C ha⁻¹ | Increased | 139%     | [159]      |
| Sand               | Column study                  | -    | Wood             | 400                         | 0% 10%                | Decreased | -92%     | [173]      |
| Clay loam          |                               |      |                  |                             | 0% 10%                | Decreased | -67%     | [173]      |
| Sand               |                               |      |                  |                             | 0% 10%                | Increased | +328%    | [173]      |
| Loam, Silt loam,   | Field 4 year                  |      | Maize            | 400                         | 0, 9.9, 18.4 Mg ha⁻¹ | Decreased | ~72 ± 3% | [175]      |
| Silty clay loam    |                               |      | Hardwood         |                             |                       | Non significant | -       | [176]      |
7. Scope of Future Research

Influence of biochar on soil physicochemical properties are mostly published from the short-term greenhouse or laboratory incubation studies. To justify the auspicious impact of biochar, long-term field studies are required for observing its interactions with soil particles. In the AWD irrigation system, soil faces periodical aerobic and anaerobic conditions, and this phenomenon changes the soil microbial community and enzymatic activities; therefore, detailed studies are necessary to investigate the effect of biochar on microbial actions and their related biochemical reactions. Moreover, interactions of biochar with soil organic matter and microbial communities concerning soil fertility and crop production in AWD conditions need to be studied. Several studies reported that AWD irrigation practice reduces CH\textsubscript{4} emission while generating an increased amount of CO\textsubscript{2}. Studies are required in order to determine the impact of biochar on mitigating this enhanced CO\textsubscript{2} emission from the AWD irrigated rice field.

A proper application method of biochar in the rice field needs to be developed to ensure its maximum effectiveness to improve soil physical properties and nutrient dynamics. Biochar is a recalcitrant material, and still, its definite service life is hardly inferred. Furthermore, an inspection of the decomposition rate of biochar in soil is obligatory. Consecutively, the residual effect of biochar in soil should be considered to escape its negative impacts. Research on the beneficial effects of biochar in a problematic or degraded soil (saline, sodic, compacted, eroded, low fertility, and low organic matter soils) is limited.

From previous studies, biochar rates such as 4 to 5% may improve soil physicochemical properties but might be impractical for extensive farming. More studies are required to inspect the integrated use of biochar with inorganic fertilizers; due to the processing of feedstocks and managing technology, this enormous amount of biochar production might be unrealistic. Although biochar incorporation in the soil improves its different properties, the economic viability of biochar application for large-scale rice production should be examined in detail. Moreover, critical economic analysis and estimation of production cost should be carried out for combined use of biochar with inorganic fertilizers to provide a practical recommendation.

8. Conclusions

Efficient use of water is one of the important issues for sustainable rice production under changing climatic conditions; AWD is one of the effective irrigation approaches. However, due to repeated transition between moistening and desiccation of soil in the AWD irrigation system of rice results in cracking through which nutrients preferentially losses from the topsoil; soil also loses extra surface moisture during the desiccated condition. Under this alternative aerobic and anaerobic ecosystem, native organic carbon and nitrogen of soil might be lost due to heterotrophic microbial activities. This negative impact of AWD irrigation in rice may not be visible in the short-term studies, but in the long term, it perhaps declines soil productivity. Enrichment of soil organic carbon plays a significant role in the soil’s physical and chemical properties and ultimate climate-smart crop productivity. The implication of biochar incorporation under this water-saving irrigation may effectively alleviate this hindrance. This review discussed biochar’s potential and its mechanisms involved in interacting with soil consecutively improving physicochemical properties and water retention. The reviewed studies can be opined that biochar has a large surface area with a highly developed pore structure, enriched by exchangeable nutrient elements. For instance, biochar may increase soil fertility by providing essential nutrients to the soil, reduce nutrient leaching through adsorbing in exchangeable sites, and increase soil pH due to its high liming contents. Furthermore, biochar addition enhances soil moisture retention due to its large surface area and storing water in its pore structure, which ultimately may result in increased water use efficiency of rice. The bulky and porous structure of biochar, with the high carbon content, enhances soil physical properties such as density, porosity, aggregation, etc. when interacting with soil; but mostly, application rates such as 1 to 5% is not realistic for this improvement. Nevertheless, biochar possibly improves soil
fertility and productivity in AWD water-saving irrigation, but further research is required for economic viability and considering its combined application with chemical fertilizers for sustainable rice production.

**Author Contributions:** Conceptualization, M.K.U. and M.F.S.; literature collection, A.N.A.H. and M.M.; writing—original draft preparation, A.N.A.H. and M.K.U.; writing—review and editing, M.F.S., A.M.A., M.H., and Z.M.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Agricultural Technology Program-Phase II, Bangladesh Agricultural Research Council, and Universiti Putra Malaysia, Selangor Darul Ehsan, Malaysia for the research facilities.

**Acknowledgments:** Authors are grateful to the National Agricultural Technology Program-Phase II, Bangladesh Agricultural Research Council, and the Universiti Putra Malaysia, Selangor Darul Ehsan, Malaysia, for the research facilities.

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

**References**

1. Amanullah, N.; Khan, S.-T.; Iqbal, A.; Fahad, S. Growth and Productivity Response of Hybrid Rice to Application of Animal Manures, Plant Residues and Phosphorus. *Front. Plant Sci.* 2016, 7, 1440. [CrossRef]
2. FAO. *FAO Rice Market Monitor*; FAO: Rome, Italy, 2018.
3. IRRI. *Rice Knowledge Bank*.
4. Bouman, B.A.M.; Hengsdijk, H.; Hardy, B.; Bindraban, P.S.; Tuong, T.P. Water-wise rice production. In *International Workshop on Water-Wise Rice Production*; International Rice Research Institute (IRRI): Los Baños, Philippines, 2002; p. 356.
5. Dong, N.M.; Brandt, K.K.; Sørensen, J.; Hung, N.N.; Hach, C.; Van Tan, P.S.; Dalsgaard, T. Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. *Soil Biol. Biochem.* 2012, 47, 166–174. [CrossRef]
6. Wu, X.H.; Wang, W.; Yin, C.M.; Hou, H.J.; Xie, K.J.; Xie, X.L. Water consumption, grain yield, and water productivity in response to field water management in double rice systems in China. *PLoS ONE* 2017, 12, e0189280. [CrossRef] [PubMed]
7. Lampayan, R.M.; Rejesus, R.M.; Singleton, G.R.; Bouman, B.A.M. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crop. Res.* 2015, 170, 95–108. [CrossRef]
8. Zhang, H.; Voroney, R.P.; Price, G.W. Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. *Soil Biol. Biochem.* 2015, 83, 19–28. [CrossRef]
9. Yao, F.; Huang, J.; Cui, K.; Nie, L.; Xiang, J.; Liu, X.; Wu, W.; Chen, M.; Peng, S. Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. *Field Crop. Res.* 2012, 126, 16–22. [CrossRef]
10. Khairi, M.N.; Mohd, M.S.J. Effects of Flooding and Alternate Wetting and Drying on the Yield Performance of Upland Rice. *Pertanika Trop. Agric. Sci.* 2016, 39, 299–309.
11. Xu, Y.; Ge, J.; Tian, S.; Li, S.; Nguy-Robertson, A.L.; Zhan, M.; Cao, C. Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Sci. Total Environ.* 2015, 505, 1043–1052. [CrossRef]
12. Riaz, A.; Khaliq, A.; Fiaz, S.; Noor, M.A.; Nawaz, M.M.; Mahboob, W.; Ullah, S. Weed Management in Direct Seeded Rice Grown under Varying Tillage Systems and Alternate Water Regimes. *Planta Daninha* 2018, 36, 59. [CrossRef]
13. Carrijo, D.R.; Lundy, M.E.; Linquist, B.A. Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crop. Res.* 2017, 203, 173–180. [CrossRef]
14. Tan, Z.; Lin, C.S.K.; Ji, X.; Rainey, T.J. Returning biochar to fields: A review. *Appl. Soil Ecol.* 2017, 116, 1–11. [CrossRef]
15. Garg, K.K.; Das, B.S.; Safeq, M.; Bhadoria, P. Measurement and modeling of soil water regime in a lowland paddy field showing preferential transport. *Agric. Water Manag.* 2009, 96, 1705–1714. [CrossRef]
16. Gordon, H.; Haygarth, P.M.; Bardgett, R.D. Drying and rewetting effects on soil microbial community composition and nutrient leaching. *Soil Biol. Biochem.* 2008, 40, 302–311. [CrossRef]
17. Belder, P.; Spiertz, J.H.J.; Bouman, B.A.M.; Lu, G.; Tuong, T.P. Nitrogen economy and water productivity of lowland rice under water-saving irrigation. *Field Crop. Res.* 2005, 93, 169–185. [CrossRef]
18. Abbasi, M.K.; Afzar, N.; Rahim, N. Effect of Wood Ash and Compost Application on Nitrogen Transformations and Availability in Soil-Plant Systems. *Soil Sci. Soc. Am. J.* 2013, 77, 558–567. [CrossRef]
19. Johannes, L.S.J. *Biochar for Environmental Management: Science, Technology and Implementation*; Lehmann, S.J.J., Ed.; Taylor & Francis: London, UK, 2015; ISBN 9780203762264.
20. Jien, S.-H.; Wang, C.-S. Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena* 2013, 110, 225–233. [CrossRef]
49. Chang, R.; Jin, T.; Lü, Y.; Liu, G.; Fu, B. Soil Carbon and Nitrogen Changes following Afforestation of Marginal Cropland across a Precipitation Gradient in Loess Plateau of China. *PLOS ONE* 2014, 9, e85426. [CrossRef] [PubMed]

50. Yang, S.; Peng, S.; Xu, J.; He, Y.; Wang, Y. Effects of water saving irrigation and controlled release nitrogen fertilizer managements on nitrogen losses from paddy fields. *Paddy Water Environ.* 2015, 13, 71–80. [CrossRef]

51. Pandey, A.; Mai, V.T.; Vu, D.Q.; Bui, T.P.L.; Mai, T.L.A.; Jensen, L.S.; de Neergaard, A. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agric. Ecosyst. Environ.* 2014, 196, 137–146. [CrossRef]

52. Hoang, T.T.H.; Do, D.T.; Tran, T.T.G.; Ho, T.D.; Rehman, H.U. Incorporation of rice straw mitigates CH4 and N2O emissions in water saving paddy fields of Central Vietnam. *Arch. Agron. Soil Sci.* 2019, 65, 113–124. [CrossRef]

53. Barton, L.; Colmer, T.D. Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass. *Agric. Water Manag.* 2006, 80, 160–175. [CrossRef]

54. Sepaskhah, A.R.; Barzegar, M. Yield, water and nitrogen-use response of rice to zeolite and nitrogen fertilization in a semi-arid environment. *Agric. Water Manag.* 2010, 98, 38–44. [CrossRef]

55. He, Y.; Lehndorff, E.; Amelung, W.; Wassmann, R.; Alberto, M.C.; von Unold, G.; Siemens, J. Drainage and leaching losses of nitrogen and dissolved organic carbon after introducing maize into a continuous paddy-rice crop rotation. *Agric. Ecosyst. Environ.* 2017, 249, 91–100. [CrossRef]

56. Kaiser, K.; Kalbitz, K. Cycling downwards–dissolved organic matter in soils. *Soil Biol. Biochem.* 2012, 52, 29–32. [CrossRef]

57. Bolan, N.S.; Adriano, D.C.; Kunhikrishnan, A.; James, T.; McDowell, R.; Senesi, N. Dissolved Organic Matter. *Global Biogeochem. Cycles* 2000, 14, 777–793. [CrossRef]

58. Keiluweit, M.; Nico, P.S.; Johnson, M.G.; Kleber, M. Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar). *Environ. Sci. Technol.* 2010, 44, 1247–1253. [CrossRef]

59. Nguyen, B.T.; Lehmann, J.; Hockaday, W.C.; Joseph, S.; Masiello, C.A. Temperature Sensitivity of Black Carbon Decomposition and Oxidation. *Environ. Sci. Technol.* 2010, 44, 3324–3331. [CrossRef]

60. Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G.; Morgan, T.J. An overview of the organic and inorganic phase composition of biomass. *Fuel* 2012, 94, 1–33. [CrossRef]

61. Schmidt, M.W.I.; Noack, A.G. Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Soil Biol. Biochem.* 2012, 52, 29–32. [CrossRef]

62. Nartey, O.D.; Zhao, B. Biochar Preparation, Characterization, and Adsorptive Capacity and Its Effect on Bioavailability of Contaminants: An Overview. *Adv. Mater. Sci. Eng.* 2014, 2014, 1–12. [CrossRef]

63. Bolan, N.S.; Adriano, D.C.; Kunhikrishnan, A.; James, T.; McDowell, R.; Senesi, N. Dissolved Organic Matter. *Adv. Mater. Sci. Eng.* 2012, 2012, 2657–2668. [CrossRef]

64. Sepaskhah, A.R.; Barzegar, M. Yield, water and nitrogen-use response of rice to zeolite and nitrogen fertilization in a semi-arid environment. *Agric. Water Manag.* 2010, 98, 38–44. [CrossRef]

65. Kaiser, K.; Kalbitz, K. Cycling downwards–dissolved organic matter in soils. *Soil Biol. Biochem.* 2012, 52, 29–32. [CrossRef]

66. Bolan, N.S.; Adriano, D.C.; Kunhikrishnan, A.; James, T.; McDowell, R.; Senesi, N. Dissolved Organic Matter. *Global Biogeochem. Cycles* 2000, 14, 777–793. [CrossRef]

67. Keiluweit, M.; Nico, P.S.; Johnson, M.G.; Kleber, M. Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar). *Environ. Sci. Technol.* 2010, 44, 1247–1253. [CrossRef]

68. Nguyen, B.T.; Lehmann, J.; Hockaday, W.C.; Joseph, S.; Masiello, C.A. Temperature Sensitivity of Black Carbon Decomposition and Oxidation. *Environ. Sci. Technol.* 2010, 44, 3324–3331. [CrossRef]

69. Vassilev, S.V.; Baxter, D.; Andersen, L.K.; Vassileva, C.G.; Morgan, T.J. An overview of the organic and inorganic phase composition of biomass. *Fuel* 2012, 94, 1–33. [CrossRef]

70. Rawat, J.; Saxena, J.; Sanwal, P. Biochar: A Sustainable Approach for Improving Plant Growth and Soil Properties. *In Biochar-an Imperative Amendment for Soil and the Environment*; IntechOpen: London, UK, 2019.

71. Tomczyk, A.; Sokolowska, Z.; Boguta, P. Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. *Rev. Environ. Sci. Biol. Technol.* 2020, 19, 191–215. [CrossRef]

72. Nartey, O.D.; Zhao, B. Biochar Preparation, Characterization, and Adsorptive Capacity and Its Effect on Bioavailability of Contaminants: An Overview. *Adv. Mater. Sci. Eng.* 2014, 2014, 1–12. [CrossRef]

73. Jatav, H.S.; Singh, S.K.; Jatav, S.S.; Rajput, V.D.; Parihar, M.; Mahawer, S.K.; Singhal, R.K. Sukirtee Importance of Biochar in Agriculture and Its Consequence. In *Applications of Biochar for Environmental Safety*; Abbas, A.A.A., Ed.; IntechOpen: London, UK, 2020.

74. Shaky, A.; Agarwal, T. Poultry Litter Biochar: An Approach towards Poultry Litter Management–A Review. *Int. J. Curr. Microbiol. Appl. Sci.* 2017, 6, 2657–2668. [CrossRef]

75. Sultana, W.; Harsh, J.B.; Abu-Lail, N.I.; Fortuna, A.-M.; Dallmeyer, I.; Garcia-Perez, M. Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. *Biomass Bioenergy* 2016, 84, 37–48. [CrossRef]

76. Lv, D.; Xu, M.; Liu, X.; Zhan, Z.; Li, Z.; Yao, H. Effect of cellulose, lignin, alkali and alkaline earth metallic species on biomass pyrolysis and gasification. *Fuel Process. Technol.* 2010, 91, 903–909. [CrossRef]

77. Nanda, S.; Mohanty, P.; Pant, K.K.; Naik, S.; Kozinski, J.A.; Dalai, A.K. Characterization of North American Lignocellulosic Biomass and Biochars in Terms of their Candidacy for Alternate Renewable Fuels. *BioEnergy Res.* 2013, 6, 663–677. [CrossRef]

78. Li, M.; Liu, M.; Li, Z.; Jiang, C.; Wu, M. Soil N transformation and microbial community structure as affected by adding biochar to a paddy soil of subtropical China. *Agric. Ecosyst. Environ.* 2016, 209, 209–219. [CrossRef]

79. Wander, M.M.; Traina, S.J.; Stinner, B.R.; Peters, S.E. Organic and Conventional Management Effects on Biologically Active Soil Organic Matter Pools. *Soil Sci. Soc. Am. J.* 1994, 58, 1130–1139. [CrossRef]

80. Yang, S.; Chen, X.; Jiang, Z.; Ding, J.; Sun, J.; Xu, J. Effects of Biochar Application on Soil Organic Carbon Composition and Enzyme Activity in Paddy Soil under Water-Saving Irrigation. *Int. J. Environ. Res. Public Health* 2020, 17, 333. [CrossRef] [PubMed]

81. Flanagan, L.B.; Johnson, B.G. Interacting effects of temperature, soil moisture and plant biomass production on ecosystem respiration in a northern temperate grassland. *Agric. For. Meteorol.* 2005, 130, 237–253. [CrossRef]

82. Borken, W.; Matzner, E. Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Glob. Chang. Biol.* 2009, 15, 808–824. [CrossRef]
Agriculture 2021, 11, 367

77. Butterly, C.R.; McNeill, A.M.; Baldock, J.A.; Marschner, P. Rapid changes in carbon and phosphorus after rewetting of dry soil. *Biol. Fertil. Soils* 2011, 47, 41–50. [CrossRef]

78. 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]

79. Lehmann, J. A handful of carbon. *Nature* 2007, 447, 143–144. [CrossRef]

80. Solaiman, Z.M.; Anawar, H.M. Application of Biochars for Soil Constraints: Challenges and Solutions. *Pedosphere* 2015, 25, 631–638. [CrossRef]

81. El-Naggar, A.; Lee, S.S.; Awad, Y.M.; Yang, X.; Ryu, C.; Rizwan, M.; Rinklebe, J.; Tsang, D.C.W.; Ok, Y.S. Influence of soil properties and feedstock on biochar performance for carbon mineralization and improvement of infertile soils. *Geoderma* 2018, 332, 100–108. [CrossRef]

82. Laird, D.A.; Fleming, P.; Davis, D.D.; Horton, R.; Wang, B.; Karlen, D.L. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma* 2010, 158, 443–449. [CrossRef]

83. Durenkamp, M.; Luo, Y.; Brookes, P.C. Impact of black carbon addition to soil on the determination of soil microbial biomass by fumigation extraction. *Soil Biol. Biochem.* 2010, 42, 2026–2029. [CrossRef]

84. El-Naggar, A.H.; Usman, A.R.A.; Al-Omran, A.; Ok, Y.S.; Ahmad, M.; Al-Wabel, M.I. Carbon mineralization and nutrient availability in calcareous sandy soils amended with woody waste biochar. *Chemosphere* 2015, 138, 67–73. [CrossRef]

85. Hussain, M.; Farooq, M.; Nawaz, A.; Al-Sadi, A.M.; Solaiman, Z.M.; Alghamdi, S.S.; Ammara, U.; Ok, Y.S.; Siddique, K.H.M. Biochar for crop production: Potential benefits and risks. *J. Soils Sediments* 2017, 17, 685–716. [CrossRef]

86. Nguyen, B.T.; Lehmann, J.; Kinyangi, J.; Smernik, R.; Riha, S.J.; Engelhard, M.H. Long-term black carbon dynamics in cultivated soil. *Biogeochemistry* 2008, 89, 295–308. [CrossRef]

87. Liang, B.; Lehmann, J.; Solomon, D.; Sohi, S.; Thies, J.E.; Skjemstad, J.O.; Luizão, F.J.; Engelland, M.H.; Neves, E.G.; Wirick, S. Stability of biomass-derived black carbon in soils. *Geochim. Cosmochim. Acta* 2008, 72, 6069–6078. [CrossRef]

88. Zimmerman, A.R.; Gao, B.; Ahn, M.-Y. Positive and negative carbon mineralization priming effects among a variety of biochar-filled soils. *Soil Biol. Biochem.* 2011, 43, 1169–1179. [CrossRef]

89. Dong, D.; Feng, Q.; McGrouther, K.; Yang, M.; Wang, H.; Wu, W. Effects of biochar amendment on rice growth and nitrogen retention in a waterlogged paddy field. *Field Crop. Res.* 2015, 153, 153–160. [CrossRef]

90. Bai, R.; Zhang, A.; Li, L.; Pan, G.; Zheng, J.; Zhang, X.; Han, X.; et al. Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles. *Field Crop. Res.* 2012, 127, 153–160. [CrossRef]

91. Haeffe, S.M.; Konboon, Y.; Wongboon, W.; Amarante, S.; Maarifat, A.A.; Knoblauch, C. Effects and fate of biochar from rice residues in rice-based systems. *Field Crop. Res.* 2011, 121, 430–440. [CrossRef]

92. Zhang, A.; Cui, L.; Pan, G.; Li, L.; Hussain, Q.; Li, L.; Zheng, J.; Zheng, J.; Zhang, X.; Han, X.; et al. Influence of soil properties and feedstock on biochar performance for carbon mineralization and improvement of infertile soils. *Geoderma* 2018, 332, 100–108. [CrossRef]

93. Wei, C.; Gao, W.; Whalley, W.R.; Li, B. Shrinkage Characteristics of Lime Concretion Black Soil as Affected by Biochar Amendment. *Pedosphere* 2018, 28, 713–725. [CrossRef]

94. Song, Y.; Rouy, Y.; Wang, G.; Yu, X. Stimulation of nitrogen turnover due to nutrients release from aggregates affected by freeze-thaw in wetland soils. *Phys. Chem. Earth Parts A* 2017, 97, 3–11. [CrossRef]

95. Liu, Y.; Lonappan, L.; Brar, S.K.; Yang, S. Impact of biochar amendment in agricultural soils on the sorption, desorption, and degradation of pesticides: A review. *Sci. Total Environ.* 2018, 645, 60–70. [CrossRef]

96. Gao, S.; DeLuca, T.H. Influence of Biochar on Soil Nutrient Transformations, Nutrient Leaching, and Crop Yield. *Adv. Plants Agric. Res.* 2016, 4, 4. [CrossRef]

97. Streubel, J.D.; Collins, H.P.; Garcia-Perez, M.; Tarara, J.; Granatstein, D.; Kruger, C.E. Influence of Contrasting Biochar Types on Five Soils at Increasing Rates of Application. *Soil Sci. Soc. Am. J.* 2011, 75, 1402–1413. [CrossRef]

98. Zimmerman, A.R.; Gao, B.; Ahn, M.-Y. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biol. Biochem.* 2010, 43, 1169–1179. [CrossRef]

99. Nelissen, V.; Rütting, T.; Huygens, D.; Staelens, J.; Ruysschaert, G.; Boeckx, P. Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. *Soil Biol. Biochem.* 2012, 55, 20–27. [CrossRef]

100. Case, S.D.C.; McNamara, N.P.; Reay, D.S.; Stott, A.W.; Grant, H.K.; Whitaker, J. Biochar suppresses N2O emissions while maintaining N availability in a sandy loam soil. *Soil Biol. Biochem.* 2015, 81, 178–185. [CrossRef]

101. El-Naggar, A.H.; Usman, A.R.A.; Al-Omran, A.; Ok, Y.S.; Ahmad, M.; Al-Wabel, M.I. Carbon mineralization and nutrient availability in calcareous sandy soils amended with woody waste biochar. *Chemosphere* 2015, 138, 67–73. [CrossRef]

102. Cayuela, M.L.; van Zwieten, L.; Singh, B.P.; Jeffery, S.; Roig, A.; Sánchez-Monedero, M.A. Biochar’s role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agric. Ecosyst. Environ.* 2014, 191, 5–16. [CrossRef]

103. Haefele, S.M.; Konboon, Y.; Wongboon, W.; Amarante, S.; Maarifat, A.A.; Knoblauch, C. Effects and fate of biochar from rice residues in rice-based systems. *Field Crop. Res.* 2011, 121, 430–440. [CrossRef]

104. Case, S.D.C.; McNamara, N.P.; Reay, D.S.; Stott, A.W.; Grant, H.K.; Whitaker, J. Biochar suppresses N2O emissions while maintaining N availability in a sandy loam soil. *Soil Biol. Biochem.* 2015, 81, 178–185. [CrossRef]
104. Ball, P.N.; MacKenzie, M.D.; DeLuca, T.H.; Montana, W.E.H. Wildfire and Charcoal Enharce Nitrification and Ammonium-Oxidizing Bacterial Abundance in Dry Montane Forest Soils. *J. Environ. Qual.* **2010**, *39*, 1243–1253. [CrossRef] [PubMed]

105. Kameyama, K.; Miyamoto, T.; Shiono, T.; Shinogi, Y. Influence of Sugarcane Bagasse-derived Biochar Application on Nitrate Leaching in Calcaric Dark Red Soi. *J. Environ. Qual.* **2012**, *41*, 1131–1137. [CrossRef] [PubMed]

106. Xie, Z.; Xu, Y.; Liu, G.; Liu, Q.; Zhu, J.; Tu, C.; Amonette, J.E.; Cadisch, G.; Yong, J.W.H.; Hu, S. Impact of biochar application on nitrogen nutrition of rice, greenhouse-gas emissions and soil organic carbon dynamics in two paddy soils of China. *Plant Soil* **2013**, *370*, 527–540. [CrossRef]

107. Knicker, H. "Black nitrogen"--an important fraction in determining the recalcitrance of charcoal. *Org. Geochem.* **2010**, *41*, 947–950. [CrossRef]

108. Steiner, C.; Glaser, B.; Teixeira, W.G.; Lehmann, J.; Blum, W.E.H.; Zech, W. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *J. Plant Nutr. Soil Sci.* **2008**, *171*, 893–899. [CrossRef]

109. Clough, T.J.; Condron, L.M. Biochar and the Nitrogen Cycle: Introduction. *J. Environ. Qual.* **2010**, *39*, 1218–1223. [CrossRef]

110. Ippolito, J.A.; Spokas, K.A.; Novak, J.M.; Lentz, R.D.; Cantrell, K.B. Biochar elemental composition and factors influencing nutrient retention. In *Biochar for Environmental Management: Science, Technology and Implementation*; Lehmann, J., Joseph, S., Eds.; Routledge: London, UK, 2015; pp. 137–161.

111. Soinne, H.; Hovi, J.; Tammeorg, P.; Turtola, E. Effect of biochar on phosphorus sorption and clay soil aggregate stability. *Geoderma* **2014**, *219–220*, 162–167. [CrossRef]

112. Yang, F.; Zhao, L.; Gao, B.; Xu, X.; Cao, X. The Interfacial Behavior between Biochar and Soil Minerals and Its Effect on Biochar Stability. *Environ. Sci. Technol.* **2016**, *50*, 2264–2271. [CrossRef] [PubMed]

113. Sukasbaye, P.; Pimthong, A.; Dhurakit, P.; Mekvichitsaeng, P.; Thiravetyan, P. Effect of biochars and microorganisms on cadmium accumulation in rice grains grown in Cd-contaminated soil. *Environ. Sci. Pollut. Res.* **2016**, *23*, 962–973. [CrossRef] [PubMed]

114. Anderson, C.R.; Condron, L.M.; Clough, T.J.; Fiers, M.; Stewart, A.; Hill, R.A.; Sherlock, R.R. Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. *Pedobiologia* **2011**, *54*, 309–320. [CrossRef]

115. Oleszczuk, P.; Josko, I.; Kuśmierz, M.; Futa, B.; Wielgosz, E.; Ligeza, S.; Pranagal, J. Microbiological, biochemical and ecotoxicological evaluation of soils in the area of biochar production in relation to polyaromatic hydrocarbon content. *Geoderma* **2014**, *213*, 502–511. [CrossRef]

116. Bhaduri, D.; Saha, A.; Desai, D.; Meena, H.N. Restoration of carbon and microbial activity in salt-induced soil by application of peanut shell biochar during short-term incubation study. *Chemosphere* **2016**, *148*, 86–98. [CrossRef] [PubMed]

117. Blackwell, P.; Joseph, S.; Munroe, P.; Anawar, H.M.; Storer, P.; Gilkes, R.J.; Solaiman, Z.M. Influences of Biochar and Biochar-Minerals on Mycorrhizal Colonisation and Nutrition of Wheat and Sorghum. *Pedosphere* **2015**, *25*, 686–695. [CrossRef]

118. Karim, A.A.; Kumar, M.; Singh, S.K.; Panda, C.R.; Mishra, B.K. Potassium enriched biochar production by thermal plasma processing of banana peduncle for soil application. *J. Anal. Appl. Pyrolysis* **2017**, *123*, 165–172. [CrossRef]

119. Martenssen, V.; Mulder, J.; Shitumbanuma, V.; Sparrevik, M.; Borrøsen, T.; Cornelissen, G. Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 681–695. [CrossRef]

120. Wang, L.; Xue, C.; Nie, X.; Liu, Y.; Chen, F. Effects of biochar application on soil potassium dynamics and crop uptake. *J. Plant Nutr. Soil Sci.* **2018**, *181*, 635–643. [CrossRef]

121. Liu, S.; Tang, W.; Yang, F.; Meng, J.; Chen, W.; Li, X. Influence of biochar application on potassium-solubilizing Bacillus mucilaginosus as potential biofertilizer. *Prop. Biochem. Biotechnol.* **2017**, *47*, 32–37. [CrossRef]

122. Wang, Y.; Yin, R.; Liu, R. Characterization of biochar from fast pyrolysis and its effect on chemical properties of the tea garden soil. *J. Anal. Appl. Pyrolysis* **2014**, *110*, 375–381. [CrossRef]

123. Chen, L.; Liu, M.; Ali, A.; Zhou, Q.; Zhan, S.; Chen, Y.; Pan, X.; Zeng, Y. Effects of Biochar on Paddy Soil Fertility Under Different Water Management Modes. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 1810–1818. [CrossRef]

124. Biederman, L.A.; Harpole, W.S. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy* **2013**, *5*, 202–214. [CrossRef]

125. Khan, S.; Chao, C.; Waqas, M.; Arp, H.P.H.; Zhu, Y.-G. Sewage Sludge Biochar Influence upon Rice (Oryza sativa L) Yield, Metal Bioaccumulation and Greenhouse Gas Emissions from Acidic Paddy Soil. *Environ. Sci. Technol.* **2013**, *47*, 8624–8632. [CrossRef] [PubMed]

126. Sun, F.; Lu, S. Biochars improve aggregate stability, water retention, and pore-space properties of clayey soil. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 26–33. [CrossRef]

127. Madiba, O.F.; Solaiman, Z.M.; Carson, J.K.; Murphy, D.V. Biochar increases availability and uptake of phosphorus to wheat under leaching conditions. *Biol. Fertil. Soils* **2016**, *52*, 439–446. [CrossRef]

128. Abirshamkesh, S.; Gorji, M.; Asadi, H.; Gh, B.-M.; Aa, P. Effects of rice husk biochar application on the properties of alkaline soil and lentil growth. *Plant Soil Environ.* **2016**, *61*, 475–482. [CrossRef]

129. Gao, T.; Gao, M.; Peng, J.; Li, N. Effects of Different Amount of Biochar on Nitrogen, Phosphorus and Potassium Nutrients in Soil. *Ser. Mater. Sci. Eng.* **2018**, *394*, 022043. [CrossRef]

130. Ahmad, M.; Lee, S.S.; Dou, X.; Mohan, D.; Sung, J.-K.; Yang, J.E.; Ok, Y.S. Effects of pyrolysis temperature on soybean stover- and peanut shell-derived biochar properties and TCE adsorption in water. *Bioresour. Technol.* **2012**, *118*, 536–544. [CrossRef]
131. Spokas, K.A.; Novak, J.M.; Venterea, R.T. Biochar’s role as an alternative N-fertilizer: Ammonia capture. *Plant Soil* **2012**, *350*, 35–42. [CrossRef]

132. Hale, S.E.; Alling, V.; Martinsen, V.; Mulder, J.; Breedveld, G.D.; Cornelissen, G. The sorption and desorption of phosphate-P, ammonium-N and nitrate-N in cacao shell and corn cob biochars. *Chemosphere* **2013**, *91*, 1612–1619. [CrossRef] [PubMed]

133. Takaya, C.A.; Fletcher, L.A.; Singh, S.; Anyikude, K.U.; Ross, A.B. Phosphate and ammonium sorption capacity of biochar and hydrochar from different wastes. *Chemosphere* **2016**, *145*, 518–527. [CrossRef] [PubMed]

134. Rogovska, N.; Laird, D.A.; Karlen, D.L. Corn and soil response to biochar application and stover harvest. *Field Crop. Res.* **2016**, *187*, 96–106. [CrossRef]

135. Gul, S.; Whalen, J.K.; Thomas, B.W.; Sachdeva, V.; Deng, H. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agric. Ecosyst. Environ.* **2015**, *206*, 46–59. [CrossRef]

136. Jaafar, N.M.; Clode, P.L.; Abbott, L.K. Biochar-Soil Interactions in Four Agricultural Soils. *Pedosphere* **2015**, *25*, 729–736. [CrossRef]

137. Purakayastha, T.J.; Bera, T.; Bhaduri, D.; Sarkar, B.; Mandal, S.; Wade, P.; Kumari, S.; Biswas, S.; Menon, M.; Pathak, H.; et al. A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: Pathways to climate change mitigation and global food security. *Chemosphere* **2019**, *227*, 345–365. [CrossRef]

138. Peng, X.; Ye, L.L.; Wang, C.H.; Zhou, H.; Sun, B. Temperature- and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. *Soil Tillage Res.* **2011**, *112*, 159–166. [CrossRef]

139. Pereira, E.I.P.; Suddick, E.C.; Mansour, I.; Mukome, F.N.D.; Parikh, S.J.; Scow, K.; Six, J. Biochar alters nitrogen transformations but has minimal effects on nitrous oxide emissions in an organically managed lettuce mesocosm. *Biol. Fertil. Soils* **2015**, *51*, 573–582. [CrossRef]

140. McKenzie, B.M.; Tisdall, J.M.; Vance, W.H. Soil Physical Quality BT-Encyclopedia of Agrophysics; Gliński, J., Horabik, J., Lipiec, J., Eds.; Springer: Dordrecht, The Netherlands, 2011; pp. 770–777. ISBN 978-90-481-3585-1.

141. Verheijen, F.; Jeffery, S.; Bastos, A.C.; Van Der Velde, M.; Diafas, I. Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions; European Commission: Luxembourg, 2010; Volume 8.

142. Alghamdi, A.G. Biochar as a potential soil additive for improving soil physical properties—a review. *Arab. J. Geosci.* **2018**, *11*, 766. [CrossRef]

143. Castellini, M.; Giglio, L.; Niedda, M.; Palumbo, A.D.; Ventrella, D. Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil Tillage Res.* **2015**, *154*, 1–13. [CrossRef]

144. Sun, Z.; Arthur, E.; de Jonge, L.W.; Elsgaard, L.; Moldrup, P. Pore Structure Characteristics After 2 Years of Biochar Application to a Sandy Loam Field. *Soil Sci.* **2015**, *180*, 41–46. [CrossRef]

145. Ball BC, S.K. Gas movement. In *Soil Analysis: Physical Methods*; Smith, K.A., Ed.; Marcel Dekker: Madison, WI, USA, 1991; pp. 511–549.

146. Schjønning, P.; Lamandé, M.; Berisso, F.E.; Simojoki, A.; Alakukku, L.; Andreasen, R.R. Gas Diffusion, Non-Darcy Air Permeability, and Computed Tomography Images of a Clay Subsoil Affected by Compaction. *Soil Sci. Soc. Am. J.* **2013**, *77*, 1977–1990. [CrossRef]

147. Ramesh, T.; Bolan, N.S.; Kirkham, M.B.; Wijesekara, H.; Kanchikerimath, M.; Rao, C.S.; Sandeep, S.; Rinklebe, J.; Ok, Y.S.; Choudhury, B.U.; et al. Chapter One-Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Adv. Agron.* **2019**, *156*, 1–107.

148. Hardie, M.; Clothier, B.; Bound, S.; Oliver, G.; Close, D. Does biochar influence soil physical properties and soil water availability? *Plant Soil* **2014**, *376*, 347–361. [CrossRef]

149. Du, Z.; Chen, X.; Qi, X.; Li, Z.; Nan, J.; Deng, J. The effects of biochar and hoggery biogas slurry on fluvo-aquic soil physical and hydraulic properties: A field study of four consecutive wheat–maize rotations. *J. Soils Sediments* **2016**, *16*, 2050–2058. [CrossRef]

150. Guo, Z.; Zhang, L.; Yang, W.; Hua, L.; Cai, C. Aggregate Stability under Long-Term Fertilization Practices: The Case of Eroded Ultisols of South-Central China. *Sustainability* **2019**, *11*, 1169. [CrossRef]

151. Hortensius, D.; Welling, R. International standardization of soil quality measurements. *Commun. Soil Sci. Plant Anal.* **1996**, *27*, 387–402. [CrossRef]

152. Cañasveras, J.C.; Barrón, V.; del Campillo, M.C.; Torrent, J.; Gómez, J.A. Estimation of aggregate stability indices in Mediterranean soils by diffuse reflectance spectrophotometry. *Geoderma* **2010**, *158*, 78–84. [CrossRef]

153. Yan, F.; Shi, Z.; Li, Z.; Cai, C. Estimating interrill soil erosion from aggregate stability of Ultisols in subtropical China. *Soil Tillage Res.* **2008**, *100*, 34–41. [CrossRef]

154. Zhang, Q.; Du, Z.; Lou, Y.; He, X. A one-year short-term biochar application improved carbon accumulation in large macroaggregate fractions. *Catena* **2015**, *127*, 26–31. [CrossRef]

155. Pal, D.K. Cracking Clay Soils (Vertisols): Pedology, Mineralogy and Taxonomy. In *A Treatise of Indian and Tropical Soils*; Springer International Publishing: Cham, Switzerland, 2017; pp. 9–42.

156. Malongwani, S.O.; Kihara, Y.; Sato, K.; Tokunari, T.; Sobuda, T.; Mrubuta, K.; Masunaga, T. Impact of agricultural waste on the shrink–swell behavior and cracking dynamics of expansive soils. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 339–349. [CrossRef]

157. Wubie, A.A. Review on vertisol management for the improvement of crop productivity in Ethiopia. *J. Biol. Agric. Healthc.* **2015**, *5*, 92–102.

158. Zong, Y.; Chen, D.; Lu, S. Impact of biochars on swell-shrinkage behavior, mechanical strength, and surface cracking of clayey soil. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 920–926. [CrossRef]
159. Herath, H.M.S.K.; Camps-Arbestain, M.; Hedley, M. Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. Geoderma 2013, 209–210, 188–197. [CrossRef]

160. Liu, X.H.; Han, Z.X. Effect of biochar on soil aggregates in the loess plateau: Results from incubation experiments. Int. J. Agric. Biol. 2012, 14, 975–979.

161. Zhang, Y.; Gu, K.; Li, J.; Tang, C.; Shen, Z.; Shi, B. Effect of biochar on desiccation cracking characteristics of clayey soils. Geoderma 2020, 364, 114182. [CrossRef]

162. Hansen, V.; Hauggaard-Nielsen, H.; Petersen, C.T.; Mikkelsen, T.N.; Müller-Stöver, D. Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types. Soil Tillage Res. 2016, 161, 1–9. [CrossRef]

163. Pardo, G.S.; Sarmah, A.K.; Orense, R.P. Mechanism of improvement of biochar on shear strength and liquefaction resistance of sand. Géotechnique 2019, 69, 471–480. [CrossRef]

164. Hodson, M.J.; White, P.J.; Mead, A.; Broadley, M.R. Phylogenetic Variation in the Silicon Composition of Plants. Ann. Bot. 2005, 96, 1027–1046. [CrossRef]

165. Currie, H.A.; Perry, C.C. Silica in Plants: Biological, Biochemical and Chemical Studies. Ann. Bot. 2007, 100, 1383–1389. [CrossRef] [PubMed]

166. Pandis, C.; Spanoudaki, A.; Kyritsis, A.; Pissis, P.; Hernández, J.C.R.; Ribelles, J.L.G.; Pradas, M.M. Water sorption characteristics of poly(2-hydroxyethyl acrylate)/silica nanocomposite hydrogels. J. Polym. Sci. Part B Polym. Phys. 2011, 49, 657–668. [CrossRef]

167. Khan, M.; Shah, M.R. Sorption kinetics of water vapours in chromatographic silica gel. J. Chem. Soc. Pak. 2007, 29, 209–212.

168. Bordoloi, S.; Gopal, P.; Boddu, R.; Wang, Q.; Cheng, Y.-F.; Garg, A. Soil-biochar-water interactions: Role of biochar from Eichhornia crassipes in influencing crack propagation and suction in unsaturated soils. J. Clean. Prod. 2019, 210, 847–859. [CrossRef]

169. Kameyama, K.; Miyamoto, T.; Iwata, Y.; Shiono, T. Effects of Biochar Produced From Sugarcane Bagasse at Different Pyrolysis Temperatures on Water Retention of a Calcaric Dark Red Soil. Soil Sci. 2016, 181, 20–28. [CrossRef]

170. Haque, A.N.A.; Uddin, M.K.; Sulaiman, M.F.; Amin, A.M.; Hossain, M.; Zaibon, S.; Mosharrof, M. Assessing the Increase in Soil Moisture Storage Capacity and Nutrient Enhancement of Different Organic Amendments in Paddy Soil. Agriculture 2021, 11, 44. [CrossRef]

171. Amoozegar, A.; Warrick, A.W. Hydraulic Conductivity of Saturated Soils: Field Methods. In Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods; Klute, A., Ed.; ASA: Madison, WI, USA, 1986; pp. 735–770.

172. Blanco-Canqui, H. Biochar and Soil Physical Properties. Soil Sci. Soc. Am. J. 2017, 81, 687–711. [CrossRef]

173. Barnes, R.T.; Gallagher, M.E.; Masiello, C.A.; Liu, Z.; Dugan, B. Biochar-Induced Changes in Soil Hydraulic Conductivity and Dissolved Nutrient Fluxes Constrained by Laboratory Experiments. PLoS ONE 2014, 9, e108340. [CrossRef]

174. Chen, C.; Wang, R.; Shang, J.; Liu, K.; Irshad, M.K.; Hu, K.; Arthur, E. Effect of Biochar Application on Hydraulic Properties of Sandy Soil under Dry and Wet Conditions. Vadose J. 2018, 17, 180101. [CrossRef]

175. Liu, Z.; Dugan, B.; Masiello, C.A.; Barnes, R.T.; Gallagher, M.E.; Gonnermann, H. Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar–sand mixtures. J. Hydrol. 2016, 533, 461–472. [CrossRef]

176. Rogovska, N.; Laird, D.A.; Rathke, S.J.; Karlen, D.L. Biochar impact on Midwestern Mollisols and maize nutrient availability. Geoderma 2014, 230–231, 340–347. [CrossRef]