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Review

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

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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

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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 increasing water scarcity for agriculture because of climate change and fast industrialization and urbanization [6]. Thus, it is crucial to adopt a substitutional irrigation system to save water without affecting rice yield under this climatic condition. To counteract this water scarcity of irrigation, International Rice Research Institute (IRRI) generated the technology of alternate wetting and drying (AWD) irrigation system for rice [7]. 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 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 upto 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.

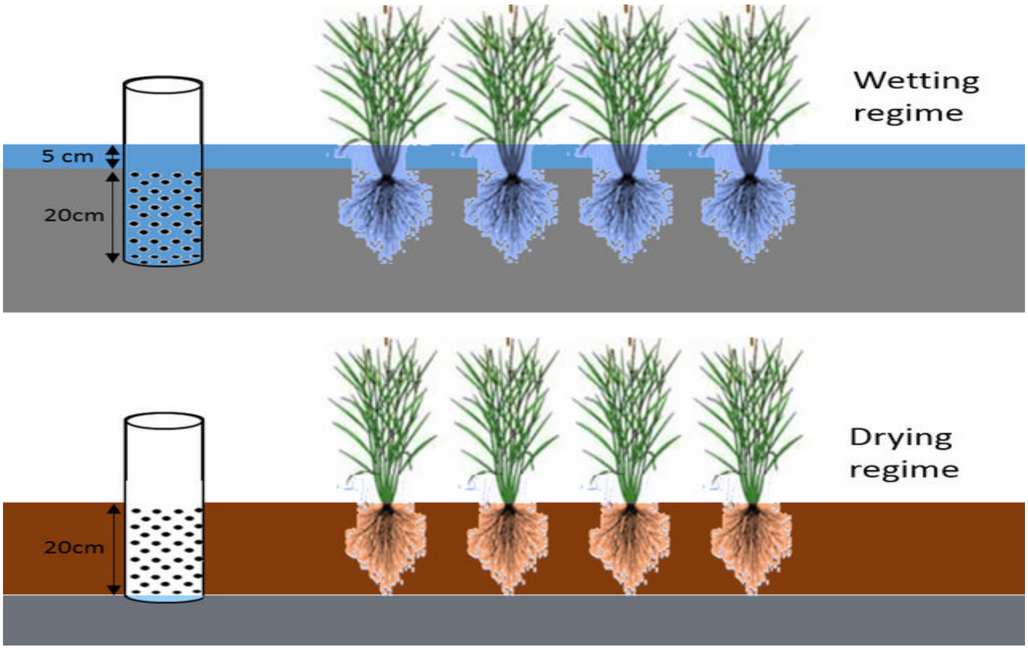

Figure 1. Alternate wetting and drying (AWD) irrigation of rice (Image collected from Riaz et al. [12]).

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 production 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 theatrical 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_2O 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.

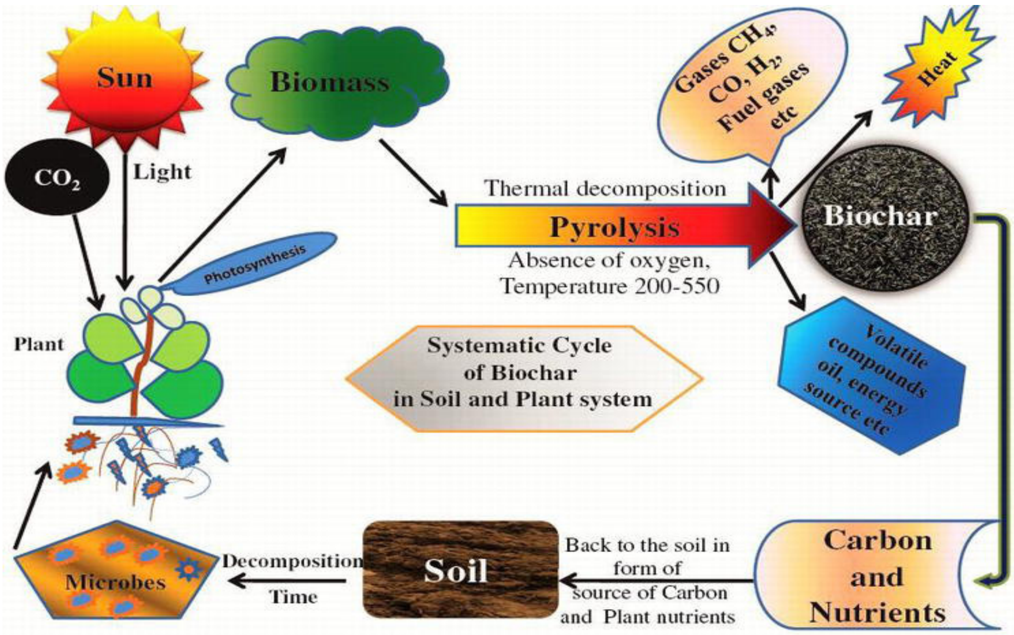

Figure 2. Systemic potential mechanism of biochar in soil and plant system (image collected from Jatav et al. [67]).

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	Chemical Properties						
	%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 Sandy loam	Incubation 6 months	-	Rice husk	~600	(% *w*/*w*) Control (0) 0.1 0.5 1.0	Soil organic C (%) 0.86ef 0.93de 0.99d 1.23a 0.80f 0.93de 1.08c 1.32a	- 8 15 43 - 16 35 65	[29]
Hydromorphic paddy soil	Pot 4 months	Rice	Rice straw	-	i. Biochar (0, 20, 40 t ha^{-1}) with controlled irrigation ii. Biochar (40 t ha^{-1}) with flooded irrigation	Greatly affected in water saving irrigation	Increased by 4 to 26.7%	[74]
Entic Halpudept	Field 2 consecutive cycles	Rice	Wheat straw	350–550	0 t ha^{-1} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1}	Soil organic C (g kg^{-1}) 1st cycle 23.2c 27.1b 29.5b 36.0a 2nd cycle 23.5b 25.7ab 28.9ab 36.1a	Increased 16.8% 27.2% 55.2% 9.4% 23.0% 53.6%	[88]
Clay loam	Field 2 crop cycles	Rice	Bamboo chips and Rice straw	600	Control (No biochar and urea) Bamboo biochar (2.25 t ha^{-1}) Rice straw biochar (2.25 t ha^{-1}) Control + urea (435 kg ha^{-1}) Bamboo biochar + urea Rice straw biochar + urea	Soil organic C (g kg^{-1}) 15.2b 24.73a 21.21a 14.18b 24.08a 20.89a	 62.7% 39.5% −6.7% 58.4% 37.4%	[89]

Table 2. *Cont.*

Soil Type	Experiment Type and Duration	Crop	Biochar Material	Pyrolysis Temperature (°C)	Biochar Rate/Treatment	Effect	% Change	References
Entic Halpudept	Field 1 growth cycle	Rice and Wheat	Municipal biowaste	450–550	0 t ha^{-1} 40 t ha^{-1}	(SOC g kg^{-1}) Rice 26.8b 32.2a Wheat (SOC) 25.2b 29.9a	Increased 21% (rice) and 19% (wheat)	[90]
Anthraquic Gleysols (Clay)	Field, 2 year	Rice	Rice husk (RH)	-	Control Control + fertilizer RHB (4.13 kg m^{-2}) RHB (4.13 kg m^{-2}) +fertilizer Untreated Rice husk Untreated Ricehusk + fertilizer	SOC (g kg^{-1}) 15.40b 14.90b 28.30a 28.70a 16.30b 16.40b	- −3.2% +83.7% +86.3% +5.8% +6.4%	[91]
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}	(SOC g kg^{-1}) 23.5b 25.9b 36.9a 23.2b 27.1b 36.0a	Increased +2% +45% +17% +55%	[92]

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_2O, 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, pyrrols, 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).

Total Nitrogen (TN)								
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} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1}	0.28a 0.29a 0.28a 0.30a	- 3.6% 0.0% 7.1%	[22]
China Entic Halpudept	Field 2 consecutive cycles	Rice	Wheat straw	350–550	0 t ha^{-1} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1}	1st cycle 2.07b 2.19b 2.11b 2.54a 2nd cycle 1.98b 1.95b 2.16ab 2.27a	+5.8% +1.9% +22.7% −1.5% +9.1% +14.6%	[88]
Clay loam	Field 2 crop cycles	Rice	Bamboo chips and Rice straw	600	Control (No biochar and urea) Bamboo biochar (2.25 t ha^{-1}) Rice straw biochar (2.25 t ha^{-1}) Control + urea (435 kg ha^{-1}) Bamboo biochar + urea Rice straw biochar + urea	2.13bc 2.32ab 2.38a 2.08c 2.17abc 2.39a	- +8.9% +11.7% −2.3% +1.9% +12.2%	[89]
Anthraquic Gleysols (Clay)	Field, 2 year	Rice	Rice husk	-	Control Control + fertilizer RHB (4.13 kg m^{-2}) RHB (4.13 kg m^{-2}) +fertilizer Untreated rice husk Untreated rice husk + fertilizer	1.41b 1.39b 1.64a 1.63a 1.46b 1.48b	- −1.42% +16.31% +15.60% +3.55% +4.96%	[91]

Table 3. *Cont.*

Total Nitrogen (TN)								
Soil Type	**Experiment Type and Duration**	**Crop**	**Biochar Material**	**Pyrolysis Temperature (°C)**	**Biochar Rate/Treatment**	**Effects**	**% Change**	**References**
EnticHalpudept	Field 4 months	Rice	Wheat straw	350–550	i. Without N	(TN g kg^{-1})		[92]
					0 t ha^{-1} 10 t ha^{-1} 40 t ha^{-1}	1.78d 2.12bcd 2.48ab	+19% +39%	
					i. With N			
					0 t ha^{-1} 10 t ha^{-1} 40 t ha^{-1}	2.07cd 2.19abc 2.54a	+6% +23%	
Acidic soil	Greenhouse 13 weeks	Rice	Sewage sludge	550	0 g kg^{-1} 5 g kg^{-1} 10 g kg^{-1}	0.04 0.18 0.26	+350% +550%	[125]
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}) Rice straw biochar (RSB) (0, 5, 10, 20, 50 g kg^{-1})	RHB and RSB increased up to 41% and 83% in sandy and, 23% and 66%in silty soil respectively	-	[123]
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	+16%, +11% and +14% by SB, WCB and WWB respectively	[126]

Table 3. *Cont.*

Phosphorus (P)								
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} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1}	71.09ab 67.36b 72.71ab 100.01a	 −5.2% +2.3% +40.7%	[22]
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	-		Available P		[91]
					Control Control + fertilizer RHB (4.13 kg m^{-2}) RHB (4.13 kg m^{-2}) + fertilizer Untreated Rice husk Untreated Rice husk + fertilizer	13.30bc 15.00a 14.70ab 15.70a 13.30bc 15.00a	- +12.78% +10.53% +18.05% +0.00% +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}) Rice straw biochar (RSB) (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) 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	+79%, +15% and +153% by SB, WCB and WWB respectively	[126]
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.*

Potassium (K)								
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} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1}	0.09c 0.13bc 0.15ab 0.19a	 +44.4% +66.7% +111.1%	[22]
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} 40 t ha^{-1}	(mg kg^{-1}) Rice 116b 148a Wheat 106b 129a	Increased 26% (rice) and 22% (wheat)	[90]
Anthraquic Gleysols (Clay)	Field, 2 year	Rice	Rice husk	-	Control Control + fertilizer RHB (4.13 kg m^{-2}) RHB (4.13 kg m^{-2}) + fertilizer Untreated rice husk Untreated ricehusk + fertilizer	(cmol kg^{-1}) 1.59b 1.65ab 1.70a 1.68ab 1.71a 1.70a	- +3.77% +6.92% +5.66% +7.55% +6.92%	[91]
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	550	(% *w*/*w*) (0, 0.5, 1, 2, 4)	Maximum increased by 4% rate	6.7 folds	[122]

Table 3. *Cont.*

Potassium (K)								
Location and Soil type	**Experiment type and duration**	**Crop**	**Biochar material**	**Pyrolysis Temperature (°C)**	**Biochar rate/treatment**	**Effects**	**% Change**	**References**
China Acidic soil	Greenhouse 13 weeks	Rice	Sewage sludge	550	0 g kg^{-1} (Control) 5 g kg^{-1} 10 g kg^{-1}	(mg kg^{-1}) 305 315 374	Increased +3% +23%	[125]
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}) 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]
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% 137	[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_3^-, 15.7% of NH_4^+, and 3.1% PO_4^{3-} effectively absorbed by biochar. Thus, it is essential to understand the mechanisms of nutrient adsorption by biochar, for example, adsorption of NH_4^+ ion on biochar surfaces due to physical adsorption [8], negatively charged surfaces absorbed NH_4^+ [88], the formation of amine and amides by the reaction of NH_4^+ against acidic functional group [131], and cationic sites of biochar surface fixed NH_4^+ [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_3^-, PO_4^{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].

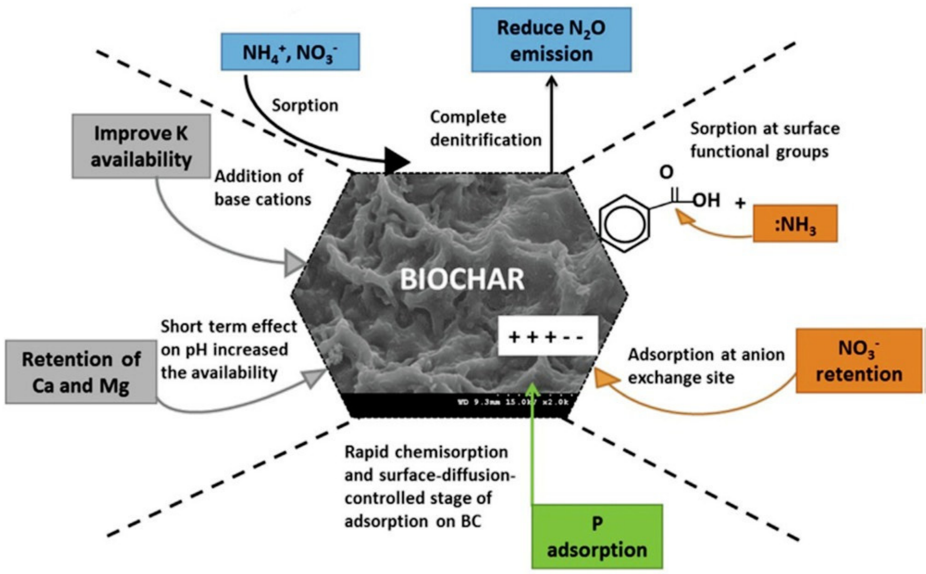

Figure 3. Schematic diagram representing how biochar improves the retention of nutrients and increases their availability in soils (Reprinted from Chemosphere, 227, Purakayastha, T.J. et al., A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: Pathways to climate change mitigation and global food security, 345–365, Copyright (2019), with permission from Elsevier. [137]).

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).

CEC ($cmol_c\ kg^{-1}$)								
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} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1}	24.26b 24.70ab 25.13ab 26.10a	 +1.8% +3.6% +7.6%	[22]
Sand Sandy loam	Incubation 6 months	-	Rice husk	~600	(% *w*/*w*) 0 0.1 0.5 1.0	Increased significantly ($p < 0.05$)	+17% +30% +31% +2% +4% +17%	[29]
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}) Rice straw biochar (RSB) (0, 5, 10, 20, 50 g kg^{-1})	Higher dose of biochar increased CEC value in both soils	Increased up to 40%	[123]
China Ultisol	Incubation 11 days	-	Rice straw	250 300 350 400 450	(% *w*/*w*) 0% (Control) 1%	Significantly ($p < 0.05$) increased	+4–17%	[138]
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.

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).

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	Rate: (% m/m) 0 0.5 1 2 4	 1.8 1.59a 1.54b 1.46c 1.33d	 - −11% −14% −19% −26%	[28]
Sand Sandy loam	Incubation 6 months	-	Rice husk	~600	(% w/w) Control (0) 0.1 0.5 1.0 Control (0) 0.1 0.5 1.0	 1.48a 1.39b 1.32c 1.27e 1.41b 1.31cd 1.28de 1.24e	 - −6 −11 −14 - −7 −9 −12	[29]
Mesic typic Happludolls	Incubation 500 days	-	Wood	-	i. Biochar (0, 5, 10, 20 g kg^{-1}) without manure ii. Biochar (0, 5, 10, 20 g kg^{-1}) manure	Non significant	-	[82]
Entic Halpudept	Field 2 consecutive cycles	Rice	Wheat straw	350–550	 0 t ha^{-1} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1} 0 t ha^{-1} 10 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1}	1st cycle 0.99 0.96 0.91 0.89 2nd cycle 0.94 0.91 0.86 0.88	 −3.0% −8.1% −10.1% −3.2% −8.5% −6.4%	[88]

Table 5. *Cont.*

Soil Type	Experiment Type and Duration	Crop	Biochar Material	Pyrolysis Temperature (°C)	Biochar Rate	Effect	% Change	References
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} ii. With N 0 t ha^{-1} 10 t ha^{-1} 40 t ha^{-1}	 1.01a 0.98ab 0.89c 0.99ab 0.96ab 0.89c	 −3% −12% −3% −10%	[92]
Sandy	Field 2 year	Maize	Birch wood	500	0 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1} 100 t ha^{-1}	Decreased	Up to −16%	[144]
Loam	Field 4 year		Peanut shell	350–500	0 Mg ha^{-1} 28 Mg ha^{-1}	1.36a 1.31b	−4%	[149]

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	% Change	References
Soil texture (Loamy sand)	Incubation 4 months	-	Winter wheat and Miscanthus	300	Rate: (*w*/*w*) 0% 0.5% 1% 2% 4%	Total porosity (cm^3 cm^{-3}) 0.322 0.395d 0.414c 0.442b 0.489a	 - +23 +29 +37 +52	[28]

Table 6. *Cont.*

Soil Type	Experiment Type and Duration	Crop	Biochar Material	Pyrolysis Temperature (°C)	Biochar Rate	Effect	% Change	References
Sand Sandy loam	Incubation 6 months	-	Rice husk	~600	(% *w*/*w*) Control (0) 0.1 0.5 1.0	% Porosity 44.02e 47.42d 50.06c 52.2a 46.79d 50.56bc 51.82ab 53.08a	- +8% +14% +19% - +8% +11% +13%	[29]
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	100%, 68% and 36% by SB, WCB and WWB respectively	[126]
Vertisol (Clay)	Column study 2.5 years	-	Fruit tree	500	0% 1% 3%	Increased significantly ($p < 0.05$)	- +13% +37%	[143]
Sandy	Field 2 year	Maize	Birch wood	500	0 t ha^{-1} 20 t ha^{-1} 40 t ha^{-1} 100 t ha^{-1}	Increased	Upto+14%	[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) 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	21%, 84% and 140% by SB, WCB and WWB respectively	[126]
China Ultisol	Incubation 11 days	-	Rice straw	250 300 350 400 450	(% w/w) 0% (Control) 1%	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 350 550	Control 7.18 t C ha^{-1}	Increased	>+17%	[159]
Andisol (Silt loam)				Control 350 550	Control 7.18 t C ha^{-1}		+7–15%	
Sandy loam	Incubation 11 months	-	Pine sawdust		0, 4, 8, 16 (g kg^{-1})	NS	-	[160]
Silt loam						Increased Significantly	+20 to +37%	

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} 50 g kg^{-1} 100 g kg^{-1} 150 g kg^{-1}	Decreased cracking area density with increasing biochar rates	33.6%, 52.1% 56.9% for 50, 100 and 150 g kg^{-1} respectively	[93]
Inceptisol Clay	Incubation 280 days			450	(*w*/*w*)	Crack area density (%)		[156]
			Rice husk		0%	12.68a		
					2%	8.87b	−30%	
					5%	6.42bc	−49%	
					10%	4.84c	−62%	
			Sugarcane bagasse		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) Wastewater biochar (WWB)	500	0 g kg^{-1} 20 g kg^{-1} 40 g kg^{-1} 60 g kg^{-1}	All biochars reduced surface crack formation	60 g kg^{-1} of SB, WCB and WWB decreased 14, 17, 19% surface area cracking density respectively	[158]
Pukou (Clay) Xiashu (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]. Głąb 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) Bamboo biochar (2.25 t ha^{-1}) Rice straw biochar (2.25 t ha^{-1}) Control + urea (435 kg ha^{-1}) Bamboo biochar + urea Rice straw biochar + urea	Soil moisture (g g^{-1}) 0.33 0.34 0.38 0.35 0.36 0.38	 +3.0% +15.2% +6.1% +9.1% +15.2%	[89]
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]
Alfisol (Silt loam) Andisol (Silt loam)	Incubation 295 days	-	Corn stover	Control 350 550 Control 350 550	Control 7.18 t C ha^{-1} 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	Effect	% Change	References
Sand Sandy loam	Incubation 6 months	-	Rice husk	~600	(% *w*/*w*) Control (0) 0.1 0.5 1.0	Decreased significantly ($p < 0.05$)	- −54 −78 - −82 −148	[29]
Kaolin clay	Column study	-	Peanut shell	500	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% +8%	[30]
Alfisol (Silt loam) Andisol (Silt loam)	Incubation 295 days	-	Corn stover	Control 350 550 Control 350 550	Control 7.18 t C ha^{-1} Control 7.18 t C ha^{-1}	Increased	139%	[159]
Sand Organic soil Clay loam	Column study	-	Wood	400	0% 10%	Decreased Decreased Increased	−92% −67% +328%	[173]
Sand	Column study	-	Wood	400	0–10% (*w*/*w*)	Decreased	~72 ± 3%	[175]
Loam, Silt loam, Silty clay loam	Field 4 year	Maize	Hardwood	400	0, 9.9, 18.4 Mg ha^{-1}	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_4 emission while generating an increased amount of CO_2. Studies are required in order to determine the impact of biochar on mitigating this enhanced CO_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.

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