A Critical-systematic review of the interactions of biochar with soils and the Observable Outcomes

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Supplementary Materials

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Text S1: Web of Science (WOS)

The WOS was chosen because a search of the word “biochar” gave significantly more hits than related databases. A search of the words “biochar” and “bio-char” in the WOS database (July 26 2021) for only research and review articles resulted in 12,565 hits (Figure 1). The popularity of biochar has grown over the years so has its economic potential. From Figure 1, it can be seen that research with biochar (based on the number of publications) was slow from 2000 to 2009 with a total number of publications of 34 as opposed to 3,009 seven years later (2010 to 2016) and 9,522 from 2017 to July 26, 2021. We infer that more people became aware of the significance of biochar (in agriculture, pollution remediation, bio-fuel production, etc.) with the expansion of the internet, and the knowledge certification that biochar can be derived from almost any waste material. With the increasing interest in biochar and its applications, there is a need for a comprehensive review of how biochar affects different soil properties, and to ascertain if these different changes correlate with the observed effects.

Text S2: Improvement of P in soils

Phosphorus (P); an essential element for a plant, is a non-renewable resource that is commonly used in agriculture. It is essential for global food security, but a lot of P is being lost thereby raising concerns about potential supplies all over the world. Biochar is considered a promising soil amendment for P management [1,2], and it is reported to have both synergistic and antagonistic effects on P dynamics (Table S5). Although P availability depends on various factors (e.g. feedstock type, pyrolysis temperature, application rate) [3–5], it was suggested that only biochar applied in quantities >10 Mg ha^{-1} and produced at temperatures <600 °C improved P availability in agricultural soils [3].

Biochar can alter the P dynamics in soil by raising the soil pH [6]. The amount of divalent cations (e.g. Ca^{2+}, Mg^{2+}) influence P availability in biochar amended soils since they can be precipitated with phosphate in soils and increase phosphate adsorption [7]. The anionic functional groups of biochar can compete with phosphate [7], thereby increasing P availability. Incorporation of biochars to soils improved soil CEC, increased soil surface repulsion for phosphate, and enhanced P availability by decreasing its adsorption [8,9]. Also, abiotic processes such as biochar-induced surface organic matter stabilization or P adsorption/desorption associated with organo-mineral complexes may regulate the change in P availability [10]. Moreover, biochar itself contains P which can be released to increase P in soils [11]. Biochar application to clay and loamy sand soils had no impact on available P [12] or the sorption of P in a tertiary ferralsol [13]. Even though applying biochar alone did not improve P content in sandy and fine texture soils, Nelson et al. [14] observed that when applied with P, biochar improved the P content in the soils. According to Bornø et al. [15], the effect of biochar on soil P was neutral in alkaline soils but positive in acidic soils. These observations indicate that the behavior of biochar in soils does not only depend on the feedstock and pyrolysis temperature but also the soil type and its basic properties. Therefore, for sustainable use of biochar, broader studies need to be carried out taking into considerations all these factors.

Text S3: The application of biochar in mitigating climate change

Text S3.1 Effect of biochar on CO_2 emission

CO_2 emission contributes about 77% of the total greenhouse gases noted to cause global warming and the CO_2 released during soil respiration is about 10-times more than that released during combustion of fossil fuels [16]. Laboratory incubation studies demonstrated that only about 1.1-2.1% of biochar C used as soil amendment was lost during the incubation time and the mean residence time of C was reduced [17]. By trapping C, biochar reduces its activity and transformation to CO_2 by 0.1-0.3 billion tons y^{-1} [18]. It was reported that the cumulative CO_2 production rate was poorly correlated with the increasing rate of biochar application to sandy loam soil [19]. According to the authors, the CO_2 emission rate was larger when the soil was treated with 1% and 2% biochar relative to control while the 10% treatment was not significantly different from the control. Also, a reduction in CO_2 emission was only observed in the 5% treatment. Although biochar increased CO_2 released from soils in the short-term, Jones et al. [15] showed using ^{14}C-labelled soil organic matter (SOM) that biochar can inhibit soil respiration and the release of CO_2 by repressing the decomposition of intrinsic SOM. The pyrolysis temperature can also influence the effect of biochar on greenhouse gas emissions. For instance, biochars produced at 350 °C were reported to induce the production of more CO_2 when added to sandy loam soils than the control, while those produced at 700 °C had no significant difference with the control [21].

Text S3.2 Effect of biochar on N_2O emission

The severity of N_2O as a greenhouse gas is about 310-times more than that of CO_2 and the use of biochars for amending soils can reduce its emission from the soil by 50-80% [22]. N_2O emission is controlled by several factors including (i) mineral N content, (ii) soil pH, (iii) decomposable organic C content, (iv) anaerobic conditions, and (v) content of denitrifying microorganisms [23]. The addition of biochar to soils has been shown to increase (a) soil pH due to its alkaline nature [24,25], (b) soil aeration, and (c) improve adsorption of NO_3^- [26]. Accordingly, by improving soil pH, biochars have the potential to suppress the production of N_2O given that a lower soil pH is favorable for mission [27]. Also, Van Zwieten et al. [28] reported that amending soils with porous biochars can increase soil aeration, thereby inhibiting the denitrification process. In their study, [29] did not observe any effect on the flux of N_2O after the addition of biochar. This observation may be related to the ability of biochar to adsorbed NO_3^- thereby inhibiting N mineralization [26] or altering the abundance of N mineralizing microorganisms [30]. In their meta-analysis and analyzing data from 261 experimental treatments and representing 30 studies (2007-2013), Cayuela et al. [31] observed that in both laboratory and field experiments, the application of biochar to soils reduced N_2O

emission by up to 54%. Interestingly, the most significant factors observed to influence N_2O emission were biochar feedstock type, biochar application rate, pyrolysis temperature, and the C/N ratios. Besides, the complex interactions of soil-biochar-N form from fertilizers also altered the N_2O emission dynamics.

Soil wetting after the application of biochar was shown to have a significant effect in suppressing the emission of N_2O [19]. Within 60 h of wetting, the authors observed that increasing the biochar application rate demonstrated a suppressing effect on N_2O emission, with 10% treatment having a suppression rate of up to 98%. Also, Wang et al. [32] investigated N_2O and CO_2 emission in and acidic soil amended with biochar combined with mineral fertilizer or an enhanced-efficiency fertilizer (urea + nitrapyrin). Over a 1-yr period, the authors observed that biochar application had minimal effect on the annual N_2O emission but suppressed emission during the cold season. They also observed that biochar did not affect yield-scaled N_2O emission when applied with mineral fertilizer as opposed to a 15% decrease when nitrapyrin was added. Additionally, biochar addition to soils increased CO_2 efflux and the organic C by 19% and 61%, respectively.

Text S3.3 Effect of biochar on CH_4 emission

Methane (CH_4) is another greenhouse gas that is more potent than CO_2 given that the radiative forcing produced per molecule is greater than that of CO_2 [33]. The use of biochar to mitigate the emission of CH_4 is greatly dependent on the soil moisture content and the microbial community structure [34]. According to them, soils can easily be transformed from CH_4 sinks to sources by increasing the moisture content. The authors also observed that the rate of CH_4 oxidation was higher at lower moisture content after treatment with biochar than without biochar, and the trend was reversed at higher moisture content. In a large scale meta-analysis, Jeffery et al. [35] observed that biochar can mitigate CH_4 emission from paddy and/or acidic soils where part of the management practice involves flooding. However, when applied to neutral or alkaline soils which have no flooding regimes, biochar can reduce their CH_4 sink potential. The authors, therefore, recommended that biochar could be a viable option to mitigate CH_4 emission in rice fields which happen to be a major source of CH_4.

Table S1. The physicochemical properties of biochar produced from various biomass precursors using varying pyrolytic conditions

Precursor	Pyrolysis temperature (ºC)	pH	Yield (%)	Ash (%)	Surface area (m^2/g)	C (%)	H (%)	O (%)	N (%)	H/C	O/C	C/N	Reference
Canola (*Brassica napus*) straw	300	8.9	41.9	14.6	1.5	58.2	-	21.6	-	-	0.371	-	[36]
	500	12.1	29.8	20.4	3.2	66.8	-	8.9	-	-	0.133	-	
Sawdust of white spruce (*Picea glauca*)	300	4.9	45.3	0.1	5.2	64.4	-	29.8	-	-	0.463	-	
	500	6.6	24.7	0.7	43	85.9	-	10.2	-	-	0.119	-	
Wheat (*Triticum aestivum*) straw	300	9.4	43.3	13	3.9	62.7	-	19.6	-	-	0.313	-	
	500	11.7	31	16.9	4.8	73.4	-	6.7	-	-	0.091	-	
Manure pellet	300	9.4	74.6	78.7	4.5	15.2	-	4.3	-	-	0.283	-	
	500	10.8	66.7	78.6	9.7	17	-	2.5	-	-	0.147	-	
Plantain peel	460	10.6	-	28	0.76	57.4	3.2	9.1	2.2	0.056	0.159	26.1	[37]
Bamboo	700	9.5	-	-	228.3	81.6	-	11.9	-	-	0.146	-	[38]
Willow wood	550	9.2	-	2.4	75.1	66.6	2.64	7.72	0.63	0.040	0.116	105.7	[39]
Cattle manure	550	9.7	-	81.7	10.4	13.4	0.51	4.01	0.78	0.038	0.299	17.2	
Corn cob	600	8.94	-	11.6	33.4	77.4	3.25	9.29	1.24	0.042	0.120	62.4	[40]
Wood	600	9.8	-	4.2	147	90	1.5	8.3	0.41	0.017	0.092	219.5	
Rice straw	600	10.4	-	-	38.8	56.4	2.1	10.51	-	0.037	0.186	-	[41]
Wood chips	600	9.6	-	-	14.8	83.3	2.89	1.53	-	0.035	0.018	-	
Manure	600	10.24	-	-	16.9	17.1	0.3	16.68	-	0.018	0.975	-	
Bamboo (*Bambusoideae*)	300	6.7	-	2.75	14.2	65.3	4.56	29.7	0.53	0.070	0.455	123.2	[42]
	600	10.2	-	4	16.9	84.3	1.93	13.2	0.6	0.023	0.157	140.5	
Sewage sludge	300	6	62.5	-	4	39.7	4.1	-	7.1	0.103	-	5.6	[43]
	500	-	28.5	-	18	9.8	0.4	1	2.1	0.041	0.102	4.7	
Peanut shell	300	7.8	36.9	1.2	3.1	68.3	3.85	25.9	1.91	0.056	0.379	35.8	[44]
	700	10.6	21.9	8.9	448.2	83.8	1.75	13.3	1.14	0.021	0.159	73.5	
Soybean stover	300	7.3	37	10.4	5.6	68.8	4.29	24.9	1.88	0.062	0.362	36.6	
	700	11.3	21.6	17.2	420.3	81.9	1.27	15.4	1.3	0.016	0.188	63.0	
Banana peel	300	-	75.3	3	8	54	6	42	1	0.111	0.778	54.0	[45]
	500	-	32.8	10.5	51	58	6	34.7	1.3	0.103	0.598	44.6	
Bamboo	600	7.9	-	-	470.4	80.9	2.43	16.5	o.15	0.030	0.204	-	[46]
Hickory wood	600	8.4	-	-	401	81.8	2.16	15.3	0.73	0.026	0.187	112.1	
Domestic wastewater sludge	400	7.3	-	37.1	-	42.7	3.4	8.1	8.1	0.080	0.190	5.3	[47]
Pine wood	450	-	44	4.6	166	81.4	3	15.3	0.3	0.037	0.188	271.3	[48]
Wheat straw	450	-	41	3.9	184	65.2	2.3	31.5	0.9	0.035	0.483	72.4	
Fescue straw	100	-	99.9	6.9	1.8	48.6	7.25	44.1	0.64	0.149	0.907	75.9	[49]
Grass (*Festuca arundinacea*)	400	-	37.2	16.3	8.7	77.3	4.7	16.7	1.24	0.061	0.216	62.3	
Wood Ponderosa pine	400	-	35.3	1.4	28.7	74.1	4.95	20.9	0.06	0.067	0.282	1235.0	

Fescue straw	500	-	-	2.1	196	81.9	3.54	14.5	0.08	0.043	0.177	1023.8	[50]
	700	-	28.8	19.3	139	94.2	1.53	3.6	0.7	0.016	0.038	134.6	
Oak bark	450	-	-	11.1	1.9	71.2	2.63	12.9	0.46	0.037	0.181	154.8	
Oak wood	450	-		2.9	2.7	82.8	2.7	8.05	0.31	0.033	0.097	267.1	
Cottonseed hull	200	-	83.4	3.1	-	51.9	6	40.5	0.6	0.116	0.780	86.5	[51]
	800	-	24.2	9.2	322	90	0.6	7	1.9	0.007	0.078	47.4	
Orange peel	150	-	82.4	0.5	22.8	50.6	6.2	41	1.75	0.123	0.810	28.9	[52]
	700	-	22.2	2.8	201	71.6	1.76	22.2	1.72	0.025	0.310	41.6	
Rice husk	500	-	-	42.2	34.4	42.1	2.2	12.1	0.5	0.052	0.287	84.2	[53]
Mixed crop straws	500	10.2	-	-	6.95	80.1	-	16	1.53	-	0.200	52.4	[54]
Peanut shell	300	7.8	36.9	1.2	3.1	68.3	3.85	25.9	1.91	0.056	0.379	35.8	[44]
	700	10.6	21.9	8.9	448.2	83.8	1.75	13.3	1.14	0.021	0.159	73.5	
Soybean stover	300	7.3	37	10.4	5.6	68.8	4.29	24.9	1.88	0.062	0.362	36.6	
	700	11.3	21.6	17.2	420.3	81.9	1.27	15.4	1.3	0.016	0.188	63.0	
Conocarpus wastes	200	7.37	-	4.53	-	64.2	3.96	26.6	0.69	0.062	0.414	93.0	[55]
	400	9.67	-	5.27	-	76.8	2.83	14.2	0.87	0.037	0.185	88.3	
	600	12.2	-	8.56	-	82.9	1.28	6.6	0.71	0.015	0.080	116.8	
	800	12.4	-	8.64	-	85	0.62	4.9	0.9	0.007	0.058	94.4	
Poplar wood	400	9	32	3.5	3	67.3	4.42	-	0.78	0.066	-	86.3	[56]
Wheat straw	400	9.1	34	9.7	4.8	65.7	4.05	-	1.05	0.062	-	62.6	
	525	9.2	-	12.7	14.2	74.4	2.83	-	1.04	0.038	-	71.5	
Spruce wood	400	6.9	36	1.9	1.8	63.5	5.48	-	1.02	0.086	-	62.3	
	525	8.6	-	4.7	40.4	78.3	3.04	-	1.17	0.039	-	66.9	
Coconut coir	350	8	30.6	22.27	-	49.7	4.5	44.45	1.14	0.091	0.894	43.6	[57]
	750	10.1	25.6	15.6	-	80.69	2.55	15.81	0.79	0.032	0.196	102.1	
Groundnut shell	350	7.7	48.5	19.3	-	56.2	5.61	37.24	0.86	0.100	0.663	65.3	
	750	9.5	38.5	10.2	-	83.49	2.39	13.47	0.58	0.029	0.161	143.9	
Buckwheat husk	350 - 650	9.23 - 10	28.5-46.3	4.02-33.1	11.4-17.8	70.1-83.9	1.81-4.44	13.3-24.4	0.89-0.99	0.026-0.053	0.19-0.291	-	[58]
Mulberry wood	350 - 650	10.2 – 11.1	22.8-37.5	7.52-9.82	19-23.3	67.9-80.1	1.63-4.53	16.6-25.2	1.58-2.16	0.024-0.053	0.244-0.315	-	
Peanut shell	350 - 650	10.4 – 11.1	29.4-45.7	7.06-24.4	14.1-28.1	64.3-74.6	1.81-4.32	21.7-29.4	1.58-1.69	0.028-0.058	0.337-0.394	-	
Sewage sludge	300	6	62.5	-	4	39.7	4.1	-	7.1	0.103	-	5.6	[43]
	500	-	28.5	-	18	9.8	0.4	-	2.1	0.041	-	4.7	
Peanut shell	300	7.8	36.9	1.2	3.1	68.3	3.85	25.9	1.91	0.056	0.379	35.8	[44]
	700	10.6	21.9	8.9	448.2	83.8	1.75	13.3	1.14	0.021	0.159	73.5	
Soybean stover	300	7.3	37	10.4	5.6	68.8	4.29	24.9	1.88	0.062	0.362	36.6	
	700	11.3	21.6	17.2	420.3	81.9	1.27	15.4	1.3	0.016	0.188	63.0	
Conocarpus wastes	200	7.37	-	4.53	-	64.2	3.96	26.6	0.69	0.062	0.414	93.0	[55]
	400	9.67	-	5.27	-	76.8	2.83	14.2	0.87	0.037	0.185	88.3	

	600	12.2	-	8.56	-	82.9	1.28	6.6	0.71	0.015	0.080	116.8	
	800	12.4	-	8.64	-	85	0.62	4.9	0.9	0.007	0.058	94.4	
Poplar wood	400	9	32	3.5	3	67.3	4.42	-	0.78	0.066	-	86.3	
Wheat straw	400	9.1	34	9.7	4.8	65.7	4.05	-	1.05	0.062	-	62.6	
	525	9.2	-	12.7	14.2	74.4	2.83	-	1.04	0.038	-	71.5	[56]
Spruce wood	400	6.9	36	1.9	1.8	63.5	5.48	-	1.02	0.086	-	62.3	
	525	8.6	-	4.7	40.4	78.3	3.04	-	1.17	0.039	-	66.9	
Coconut coir	350	8	30.6	22.27	-	49.7	4.5	44.45	1.14	0.091	0.894	43.6	
	750	10.1	25.6	15.6	-	80.69	2.55	15.81	0.79	0.032	0.196	102.1	[57]
Groundnut shell	350	7.7	48.5	19.3	-	56.2	5.61	37.24	0.86	0.100	0.663	65.3	
	750	9.5	38.5	10.2	-	83.49	2.39	13.47	0.58	0.029	0.161	143.9	
Poultry litter	350	8.7	54.3	30.7	3.9	51.1	3.79	15.6	4.45	0.074	0.305	11.5	[59]
	700	10.3	36.7	46.2	50.9	45.9	1.98	10.5	2.07	0.043	0.229	22.2	
Rice straw	300	9.2	49.8	24.2	-	74.7	5.09	18.5	1.72	0.068	0.248	43.4	[60]
	700	10.7	34.7	29.3	-	90.6	1.8	6.2	1.41	0.020	0.068	64.3	
Banana peel	300	-	75.3	3	8	54	6	42	1	0.111	0.778	54.0	[45]
	500	-	32.8	10.5	51	58	6	34.7	1.3	0.103	0.598	44.6	
Canola (*Brassica napus*) straw	180	6.3	60.5	8.1	4.36	53.2	5.2	32.9	1.3	0.098	0.618	40.9	
	240	6	42.5	5.6	3.42	68.1	5.5	18.5	2.1	0.081	0.272	32.4	
	300	6.8	25.5	7.2	1.76	72	5.1	13.9	2.1	0.071	0.193	34.3	
Sawdust of white spruce (*Picea glauca*)	180	3.6	72	0.4	2.71	66.6	4.6	28.2	0.2	0.069	0.423	333.0	
	240	3.3	54.5	0	30.6	71.7	4.6	23.5	0.1	0.064	0.328	717.0	
	300	4.5	43	0.2	9.81	75.4	4.1	20.1	0.2	0.054	0.267	377.0	
Wheat (*Triticum aestivum*) straw	180	5.4	69.5	5.3	4.53	61.1	4.6	38.1	0.9	0.075	0.624	67.9	[61]
	240	5.5	42.5	6	4.54	66.7	4.5	28	0.9	0.067	0.420	74.1	
	300	5.5	30	7.9	4.07	68.9	4	21.9	1.2	0.058	0.318	57.4	
Manure pellet	180	5.5	67.5	63.8	11.7	21.3	2.2	7	1.5	0.103	0.329	14.2	
	240	6	58.5	73.2	17.6	19.8	1.6	3.9	1.7	0.081	0.197	11.6	
	300	7.3	60	77.3	11.8	17	1.4	4.2	1.3	0.082	0.247	13.1	
Rice husk	600	7.8	-	42	11	38	2.1	59	0.9	0.055	1.553	42.2	[62]
Saw dust	600	8.6	-	15	7	82	1.7	13	0.6	0.021	0.159	136.7	
Corn cob	600	8.9	-	39	123	69	3.4	17.6	6.1	0.049	0.255	11.3	[63]
Safflower seed	400	8.18	-	7.5	2.67	68.8	4.07	23.5	3.77	0.059	0.342	18.2	
	450	9.13	-	8.2	3.33	70.4	3.49	22.4	3.69	0.050	0.318	19.1	
	500	9.44	-	8.5	4.23	71.4	2.96	21.8	3.91	0.041	0.305	18.3	[64]
	550	9.67	-	8.9	3.78	73	2.67	20.6	3.74	0.037	0.282	19.5	
	600	9.89	-	9.2	3.41	73.7	2.34	20.1	3.84	0.032	0.273	19.2	
Walnut shell	900	9.7	-	40.4	227.1	55.3	0.89	1.6	0.47	0.016	0.029	117.7	[65]
Turkey litter	800	10.9	-	64	21.8	15.6	0.83	4.4	0.78	0.053	0.282	20.0	
Potato starch	700	9.7	–	20.2	-	77.1	1.08	19.7	2.17	0.014	0.256	35.5	[66]
Potato peel	700	10.9	–	25.58	-	71.5	2.41	15.8	5.2	0.034	0.221	13.8	

Digested sugar beet tailing	600	9.9	-	-	336	30.8	1.38	39.9	2.74	0.045	1.295	11.2	[67]
Sugar beet tailing	600	9.5	-	-	2.6	50.8	2.08	36.7	1.83	0.041	0.722	27.8	
Saw dust	450	5.9	-	1.1	-	72	3.5	24.4	0.08	0.049	0.339	900.0	[68]
	550	12.1	-	2.8	-	85	1	13.7	0.3	0.012	0.161	283.3	
Rice straw	600	8.83	-		65.5	59.6	-	-	1.66	-	-	35.9	[69]
Eucalyptus bark	350	7.35	-		-	-	-	-	0.52	-	-	-	[70]
Cotton sticks	450	9.5	-		-	46.3	-	-	1.12	-	-	41.3	[71]
Reed	350	7.49	-		-	67.89	-	-	0.57	-	-	119.1	[72]
Barley grass	500	9.97	-		35.4	60.9	2.42	13.3	1.07	0.040	0.218	56.9	[73]
Wheat straw	500	-	-		7.42	59.3	2.35	20.8	0.93	0.040	0.351	63.8	[74]
Rice husk	450	8.7	-		-	-	-	-	-	-	-	-	[75]
Rice straw	550	9.4	-		-	7.9	1.6	-	2.65	0.203	-	3.0	[76]
Wheat straw	600	9.2	-		-	42.8	-	-	0.27	-	-	158.5	[77]
Lemongrass	350	8.13	-		-	47.6	-	-	0.73	-	-	65.2	[78]
Woody biomass	500	9.01	-		257.3	79.8	2.01	11.9	1.65	0.025	0.149	48.4	[79]
Coconut husks	500	10.6	-		122	79.5	-	-	0.42	-	-	189.3	[80]
Orange bagasse	500	10	-		99	72.3	-	-	2.55	-	-	28.4	
Wheat straw	400	9.2	-		9	46.2	-	-	0.72	-	-	64.2	[81]
Rice straw	300	-	-		-	52	-	-	-	-	-	-	[82]
Rice hulls	500	6.96	-		95.67	33.6	2.2	13.5	0.31	0.065	0.402	108.4	[83]
Straw	700	-	-		-	81	2.5	15.6	-	0.031	0.193	-	[84]
Rice husk	700	9.42	-		406.2	45.9	2.5	26.6	0.31	0.054	0.580	148.1	[85]
Corn straw	700	10.4	-		553.8	38.84	1.4	10.03	0.39	0.036	0.258	99.6	
Rice Straw	500	9.87	-		32.2	36.6	3.7	14.6	0.41	0.101	0.399	89.3	[86]
Corn straw	500	9.97	-		9.97	57.33	1.46	4.87	0.71	0.025	0.085	80.7	
Rice straw	400-500	7.9	-		8.9	74.9	-	11.3	1.3	-	0.151	57.6	[87]
Rice straw	500	6.7	-		41	52.6	-	35.2	-	-	0.669		[88]
Rice straw	700	10.6	-		41.4	43.3	1.5	14	0.87	0.035	0.323	49.8	[89]
Rice straw	700	11.6	-		161.2	53	0.6	7.6	0.78	0.011	0.143	67.9	[90]
Rice Straw	800	12.3	-		-	58.1	1.35	12.2	1.09	0.023	0.210	53.3	[91]
Rice straw	700	-	-		369.2	31.8	0.98	7.23	0.96	0.031	0.227	33.1	[92]
Rice husk	600	-	-		168	51.8	2.05	10.4	0.56	0.040	0.201	92.5	[93]
Woodchips	600	-	-		312	85.6	2.84	9.86	0.09	0.033	0.115	951.1	
Husk	700	-	-		106.7	59.7	1.3	-	0.81	0.022	-	73.7	[94]
Husk	300	6.3	-		1.99	48.3	25.1	2.3	0.11	0.520	0.048	439.1	[95]
Olive palm	300	7.13	-		1.46	58.6	3.8	31.48	1.61	0.065	0.537	36.4	
Husk	900	-	-		179	40.9	1.2		0.47	0.029	0.000	87.0	[96]
Husk	700	9.87	-		377	47.7	1.29	7.6	0.65	0.027	0.159	73.4	[97]
Tea waste	700	10.2	-		342.22	73.6	1.71	7.67	3.39	0.023	0.104	21.7	
Rice straw	500	10	-		36.7	50.8	1.72	-	1.66	0.034	-	30.6	[98]

Bamboo	500	9.5	-		907.4	86	1.49	-	0.45	0.017	-	191.1	
Husk	700	9.94	-		42	47.3	0.63	2.06	0.85	0.013	0.044	55.6	[99]
Wheat straw pellets	550	9.81	-		26.4	68.3	2.1	6.9	1.39	0.031	0.101	49.1	
Rice husk	550	-	-		-	50.9	2	10.1	-	0.039	0.198	-	[100]
Peanuts shell	500	-	-		2.49		3.2	10.8	-	-	-	-	
Rice husk	500	-	-		1.85		2.8	15	-	-	-	-	[101]
Corn cobs	500	-	-		5.48		3.7	13.3	-	-	-	-	
Canola straw	350	8	24.4	25	-	-	-	-	-	-	-	364	
Wheat straw	350	6.42	24.8	30.3	-	-	-	-	-	-	-	143	
Rice straw	350	7.69	33.3	40.3	-	-	-	-	-	-	-	26	
Rice chaff	350	6.43	34.1	29.3	-	-	-	-	-	-	-	20	
Corn straw	350	9.24	30.8	33.7	-	-	-	-	-	-	-	20	
Soybean straw	350	9.02	32.5	23.3	-	-	-	-	-	-	-	15	[102]
Peanut straw	350	8.88	39.4	40.9	-	-	-	-	-	-	-	17	
Faba bean straw	350	10.33	26.3	24.1	-	-	-	-	-	-	-	26	
Pea straw	350	10.26	30.2	29.8	-	-	-	-	-	-	-	13	
Mung bean straw	350	10.35	31.3	33.3	-	-	-	-	-	-	-	33	

Table S2. Estimated chemical properties of biochar

Biochar	Pyrolysis temperature (oC)	pH	Alkalinity (cmol+ kg^{-1})	CEC (cmol+ kg^{-1})	Functional groups (cmol kg^{-1})			Sum of exchangeable base cations (Mg, Ca, K, Na) (cmol$_c$ kg^{-1})	References
					Phenolic	Lactonic	Carboxylic		
Corn stover	400	9.19	148.1	132.5	59	42	53.9	84.3	
Canolar stover	400	7.95	136.3	138.6	106.7	35.9	44.4	86.8	[24]
Peanut stover	400	10.28	321.3	146.8	80.4	51	63.5	146.9	
Rice straw	400	10.01	179.2	143.2	48.1	44.9	51.5	81.5	

Canola straw	350	-	183	-	143	32	12.1	-	[103]
Peanut straw	350	-	299	-	160	37	6.4	-	
Canola straw	350	8	-	180	-	-	-	-	[104]
Rice straw	350	7.69	-	152	-	-	-	-	
Soybean straw	350	9.02	-	98	-	-	-	-	
Pea straw	350	10.26	-	104	-	-	-	-	
Canola straw	350	8	191.4	180	143	32.2	12.1	195.5	[105]
Wheat straw	350	6.42	120.1	151	116	36.5	11.5	107.8	
Rice straw	350	7.69	162.7	152	106	24.1	9	141.5	
Rice hull	350	6.43	79.8	86	87	21.2	13.4	70.8	
Corn straw	350	9.24	179.9	136	81	37.2	4.1	228	
Soybean straw	350	9.02	273.1	98	139	27.5	6.4	196.3	
Peanut straw	350	8.88	292.7	81	160	36.8	6.4	160.5	
Faba bean straw	350	10.33	216.8	99	39	15.6	1.1	219.9	
Mung bean straw	350	10.35	326.1	91	26	38.8	2.1	267	
	300	6.48	-	199	-	-	-	133	[106]
Canola straw	500	9.39	-	210	-	-	-	222	
	700	10.76	-	179	-	-	-	341	
	300	9.37	-	183	-	-	-	235	
Corn straw	500	10.77	-	304	-	-	-	351	
	700	11.32	-	210	-	-	-	524	
	300	7.66	-	279	-	-	-	157	
	500	10.92	-	216	-	-	-	248	
Soybean straw	700	11.1	-	222	-	-	-	311	
	300	8.6	-	229	-	-	-	228	
Peanut straw	500	10.86	-	230	-	-	-	366	
	700	11.15	-	254	-	-	-	424	
Rice straw	500	10	152	45	-	-	-	-	[107]
Bamboo	500	9.5	123	15	-	-	-	-	

Table S3. Effect of biochar incorporation on soil physicochemical properties

Soil type	Pyrolysis temperature (°C)	Biochar precursor	Treatment rate (%)	pH	ΔpH due to biochar	CEC (mmol kg^{-1})	% increase in CEC due to biochar	pHBC (mmol kg^{-1} pH^{-1})	% increase in pHBC due to biochar	Reference
Ultisol from tertiary red sandstone	-	Corn straw	0%	5.16	-	64.3	-	11.99		[108]
	400		3%	6.23	1.1	86.5	34.5	15.3	27.61	
	400		5%	6.65	1.5	97.5	51.6	19.43	62.05	

Ultisol from quaternary red earth	-		0%	4.78	-	127.4	-	27.25	-	
	400		3%	5.38	0.60	136.9	7.46	32.07	17.69	
	400		5%	5.70	0.92	150.3	18.0	34.67	27.23	
Ultisol from granite	-		0%	4.64	-	77.2	-	22.98	-	
	400		3%	5.12	0.48	97.5	26.3	26.13	13.71	
	400		5%	5.61	0.97	109.2	41.5	30.41	32.33	
Oxisol from basalt	-		0%	4.80	-	140.2	-	33.76		
	400		3%	5.58	0.78	160.4	14.4	38.17	13.06	
	400		5%	5.97	1.17	177.2	26.4	41.72	23.58	
Ultisol from tertiary red sandstone	-		0%	4.96	-	-	-	12.52	-	[24]
	400	Corn stover	5%	6.69	1.73	-	-	23.52	87.86	
	400	Canolar stover		6.78	1.82	-	-	23.14	84.82	
	400	Peanut stover		8.40	3.44	-	-	37.37	198.48	
	400	Rice straw		7.45	2.49	-	-	30.49	143.53	
Ultisol from tertiary red sandstone	-	Peanut straw	0%	5.16	-	-	-	12.1	-	[25]
	400		1%	6.81	1.65	-	-	13.93	15.12	
	400		3%	7.83	2.67	-	-	21.26	75.70	
Ultisol from quaternary red earth	-		0%	4.78	-	-	-	26.44	-	
	400		1%	5.21	0.43	-	-	26.71	1.02	
	400		3%	6.33	1.55	-	-	33.16	25.42	
Ultisol from quaternary red earth	-		0%	5.38	-	51.5	-	20.8	-	[103]
	350	Canola straw	3%	6.72	1.34	59	14.6	22.3	7.21	
	350		5%	7.46	2.08	61.7	19.8	27.3	31.25	
	350	Peanut straw	3%	6.83	1.45	82.6	60.4	30.5	46.63	
	350		5%	7.35	1.97	92.8	80.2	36.1	73.56	
Oxisol from Basalt	-		0%	5.05	-	59.7	-	20.1	-	
	350	Canola straw	3%	6.68	1.63	61.2	2.51	23	14.43	
	350		5%	7.29	2.24	71.4	19.6	27	34.33	
	350	Peanut straw	3%	6.85	1.80	80.1	34.2	29.4	46.27	
	350		5%	7.29	2.24	90.3	51.3	38.6	92.04	
Ultisol from granite	-		0%	5.00	-	53	-	15.5	-	
	350	Canola straw	3%	6.70	1.70	65.3	23.2	18.4	18.71	
	350		5%	7.47	2.47	70.4	32.8	23.6	52.26	
	350	Peanut straw	3%	7.04	2.04	78	47.2	25.7	65.81	
	350		5%	7.45	2.45	96.9	82.8	34.6	123.23	
Ultisol from quaternary red earth	-		0%	3.99	-	91.2	-	-	-	[104]
	350	Canola straw	1%	4.35	0.36	106.5	16.8	-	-	
	350		2%	4.65	0.66	114.1	25.1	-	-	
	350	Rice straw	1%	4.26	0.27	102	11.8	-	-	
	350		2%	4.46	0.47	107.2	17.5	-	-	
	350	Soybean straw	1%	4.49	0.50	101	10.7	-	-	

	350		2%	5.19	1.20	106	16.2	-	-	
	350	Pea	1%	4.42	0.43	99.1	8.66	-	-	
			2%	4.99	1.00	104.6	14.7	-	-	
Quaternary red soil	-		0%	4.80	-	115.9	-	-	-	[109]
	450	Fresh *P. massoniana* bark	2%	5.05	0.25	123.2	6.30	-	-	
	450	Aged *P. massoniana* bark	2%	4.98	0.18	109	-5.95	-	-	
Ultisol from quaternary red earth	-		0%	4.68		115.1	-	-	-	
	350	Rice chaff	1%	5.01	0.33	95.3	-17.2	-	-	
	350	Wheat straw	1%	4.79	0.11	110.3	-4.17	-	-	
	350	Corn straw	1%	4.69	0.01	105.8	-8.08	-	-	
	350	Faba bean straw	1%	5.23	0.55	108.1	-6.08	-	-	
	350	Peanut straw	1%	5.41	0.73	107.9	-6.26	-	-	
	350	Mungbean straw	1%	5.40	0.72	107.4	-6.69	-	-	
Oxisol from Basalt	-		0%	4.50	-	55.4	-	-	-	[105]
	350	Rice chaff	1%	4.71	0.21	64.4	16.2	-	-	
	350	Wheat straw	1%	4.72	0.22	67.1	21.1	-	-	
	350	Corn straw	1%	5.06	0.56	62.7	13.2	-	-	
	350	Faba bean straw	1%	5.42	0.92	63.6	14.8	-	-	
	350	Peanut straw	1%	5.68	1.18	66.9	20.8	-	-	
	350	Mungbean straw	1%	5.97	1.47	64.4	16.2	-	-	
Ultisol from granite	-		0%	4.40	-	71.1	-	-	-	
	350	Rice chaff	1%	4.70	0.30	69.9	-1.69	-	-	
	350	Wheat straw	1%	4.52	0.12	70.9	-0.28	-	-	
	350	Corn straw	1%	4.66	0.26	75.3	5.91	-	-	
	350	Faba bean straw	1%	5.14	0.74	74.5	4.78	-	-	
	350	Peanut straw	1%	5.33	0.93	79.2	11.4	-	-	
	350	Mungbean straw	1%	5.93	1.53	77.4	8.86	-	-	

Table S4. Effect of biochar on soil exchangeable properties

Soil type	Biochar precursor	Treatment rate (%)	Soil pH	ΔpH due to biochar	Exchangeable acidity (mmol+ kg^{-1})	% decrease in exchangeable acidity due to biochar	Exchangeable Al (mmol+ kg^{-1})	% decrease in echangeable Al due to biochar	Exchangeable base cations (mmol+ kg^{-1})	% increase in exchanegable base cations due to biochar	References

Ultisol from quaternary red earth	-	0%	4.05	-	66.1	-	57.2	-	33.3	-	[105]
	Canola straw	1%	4.56	0.51	39.9	39.64	39.7	30.59	61.1	83.48	
	Wheat straw	1%	4.3	0.25	53.6	18.91	52.7	7.87	47.7	43.24	
	Rice straw	1%	4.44	0.39	47	28.90	46.6	18.53	57.9	73.87	
	Rice chaff	1%	4.4	0.35	57.5	13.01	56.8	0.70	43.6	30.93	
	Corn straw	1%	4.37	0.32	47.6	27.99	47.2	17.48	60.6	81.98	
	Soybean straw	1%	4.74	0.69	25.1	62.03	24.4	57.34	71	113.2	
	Peanut straw	1%	4.87	0.82	27.9	57.79	26.8	53.15	72.3	117.1	
	Faba bean straw	1%	4.7	0.65	38.3	42.06	37.6	34.27	58.9	76.9	
	Pea straw	1%	4.61	0.56	31.2	52.80	30.1	47.38	70	110.2	
	Mungbean straw	1%	4.88	0.83	24.7	62.63	23.5	58.92	71	113.2	
Oxisol Chengmai	-	0%	4.5	-	54	-	46.8	-	18.4	-	
	Rice chaff	1%	4.71	0.21	34.1	36.85	27	42.31	33.5	82.07	
	Wheat straw	1%	4.72	0.22	29	46.30	21.2	54.70	42.2	129.3	
	Corn straw	1%	5.06	0.56	14.1	73.89	14.1	69.87	63.2	243.5	
	Faba bean straw	1%	5.42	0.92	10.1	81.30	10.1	78.42	62.1	237.5	
	Peanut straw	1%	5.68	1.18	13.1	75.74	13.1	72.01	60.5	228.8	
	Mungbean straw	1%	5.97	1.47	6.9	87.22	6.9	85.26	64.4	250.0	
Ultisol from granite	-	0%	4.4	-	26.6	-	25.4	-	27.9	-	
	Rice chaff	1%	4.7	0.3	18.1	31.95	17.3	31.89	44.7	60.22	
	Wheat straw	1%	4.52	0.12	17.9	32.71	17.1	32.68	43.7	56.63	
	Corn straw	1%	4.66	0.26	3.9	85.34	3.9	84.65	66.6	138.7	
	Faba bean straw	1%	5.14	0.74	3.1	88.35	3.1	87.80	55.8	100.0	
	Peanut straw	1%	5.33	0.93	1.5	94.36	1.5	94.09	62.5	124.0	
	Mungbean straw	1%	5.93	1.53	0.9	96.62	0.9	96.46	77.1	176.3	
Ultisol from quaternary red earth	-	0%	4.68	-	39.1	-	36.4	-	34.1	-	
	Rice chaff	1%	5.01	0.33	29.9	23.53	25.9	28.85	45.5	33.43	
	Wheat straw	1%	4.79	0.11	32.7	16.37	29.3	19.51	52.6	54.25	
	Corn straw	1%	4.69	0.01	18.9	51.66	16.1	55.77	67.6	98.24	
	Faba bean straw	1%	5.23	0.55	21.1	46.04	19.1	47.53	57.6	68.91	
	Peanut straw	1%	5.41	0.73	14.4	63.17	12.4	65.93	70.1	105.6	

	Mungbean straw	1%	5.4	0.72	9.2	76.47	8.1	77.75	84.1	146.6	
Ultisol from quaternary red earth	-	0%	3.99	-	49.2	-	47.6	-	50.2	-	[104]
	Canola straw	1%	4.35	0.36	34	30.89	31.5	33.82	69	37.45	
		2%	4.65	0.66	20.8	57.72	19	60.08	95.6	90.44	
	Rice straw	1%	4.26	0.27	36.1	26.63	33.8	28.99	68.2	35.86	
		2%	4.46	0.47	21.8	55.69	20.2	57.56	88.7	76.69	
	Soybean straw	1%	4.49	0.5	26.1	46.95	24	49.58	82.5	64.34	
		2%	5.19	1.2	5.5	88.82	5	89.50	116.2	131.5	
	Pea	1%	4.42	0.43	26.8	45.53	24.8	47.90	85.6	70.52	
		2%	4.99	1	6.6	86.59	5.5	88.45	118.6	136.3	
Ultisol from quaternary red soil	-	0%	4.80	-	70.2	-	67.7	-	8.8	-	[109]
	Fresh *P. massoniana* bark	2%	5.05	0.25	45.8	34.76	43.5	35.75	19.1	117.0	
	Aged *P. massoniana* bark	2%	4.98	0.18	55.7	20.66	53.3	21.27	11.5	30.68	
Ultisol from quaternary red soil	-	0%	-	-	59.5	-	58.7	-	60.4	-	[102]
	Canola straw	1%	-	-	40.5	31.93	39.1	33.39	97.8	61.92	
	Wheat straw	1%	-	-	52.7	11.43	51.1	12.95	76.4	26.49	
	Rice straw	1%	-	-	42.8	28.07	42	28.45	88.7	46.85	
	Rice hull	1%	-	-	54.4	8.57	52	11.41	70.2	16.23	
	Corn straw	1%	-	-	43.3	27.23	42.7	27.26	90	49.01	
	Soybean straw	1%	-	-	28.2	52.61	27.1	53.83	111.6	84.77	
	Peanut straw	1%	-	-	26.8	54.96	26.4	55.03	103.3	71.03	
	Faba bean straw	1%	-	-	39.3	33.95	38	35.26	92.3	52.81	
	Mungbean straw	1%	-	-	26.2	55.97	25.1	57.24	111.7	84.93	

Table S5. Impact of biochar on dynamics of soil phosphorus

Soil type	Feedstock	Production conditions	Application rate	Remarks	References
Clay and sand	A mixture of Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris L.*) chips	550–600 °C; 10-15 min	0, 15 and 30 t ha−1	P sorption in incubated soils was not increased by adding biochar.	[110]
Silty clay	Maize stalk	500 °C	0, 5 and 10 t ha^{-1}	A significant ($p < 0.01$) increase in available phosphorous	[111]
Clay and loamy sand	*Acacia nilotica* (L) Delile and *Eucalyptus obliqua* (L)	450–550 °C	0, 5, 10 and 20 t ha^{-1}	The use of biochar had no impact on available P in the soil.	[12]
Tertiary Ferralsol	Bark and sewage sludge	Low temperature	1 g C kg^{-1} soil	Biochars have no effect on the bioavailability and sorption of P.	[13]
Sandy	Forest slash (Douglas fir)	650 °C	-	Biochar amendments had no impact on phosphorus leaching.	[112]
Sandy loess soil	Chinese pine and locust	600 °C; 2 h	0 gkg^{-1}, 4 gkg^{-1}, 8 gkg^{-1} and 16 gkg^{-1}	Biochar reduced the total phosphorus in the soil.	[113]
Sandy soil and fine textured soil	Corn cobs	305 °C; 20 min	0, 2, and 20 gkg^{-1}	In the absence of P additions, biochar reduced P concentrations in soil by 0.9 mg kg^{-1}. When combined with a P source, biochar increased P levels by 3.3 mg kg^{-1}.	[14]
Sandy loam	Wood	450-550 °C	20 t ha^{-1}	A positive effect on surface soil P bioavailability	[10]
Nitisols	corn cobs, *Lantana camara* stem, *Eucalyptus globulus* feedstock	500 °C for 4 h	6, 12 and 18 t ha^{-1}	The application of biochar significantly increased available phosphorus in the soil	[114]
Sandy soil	Coffee grounds, coffee husk	530 °C, 10 to 12 h	4, 8, 12 and 16 Mg ha^{-1}	available P content increased	[115]
Sandy soil, sandy clay loam, loam silt	Pine wood chips (*Pinus spp.*), wheat straw pellets	700 °C, 1000–1200 °C	2% (w/w)	Biochar had no P effect in an alkaline soil, had positive effects in acidic soils	[15]
Red earth, Fluvo-aquic	Maize straw	400 °C, 1.5 h	2, 4, and 8% (*w/w*)	Biochar effect on soil P increased by higher biochar application rates and by lower P sorption capacity.	[116]
Loam	Chipped pine (*Pinus radiata* D. Don) branches and chipped weeping willow (*Salix matsudana* L.) branches	450 °C or 550 °C	4.5% (w/w)	Possitive effects	[117]

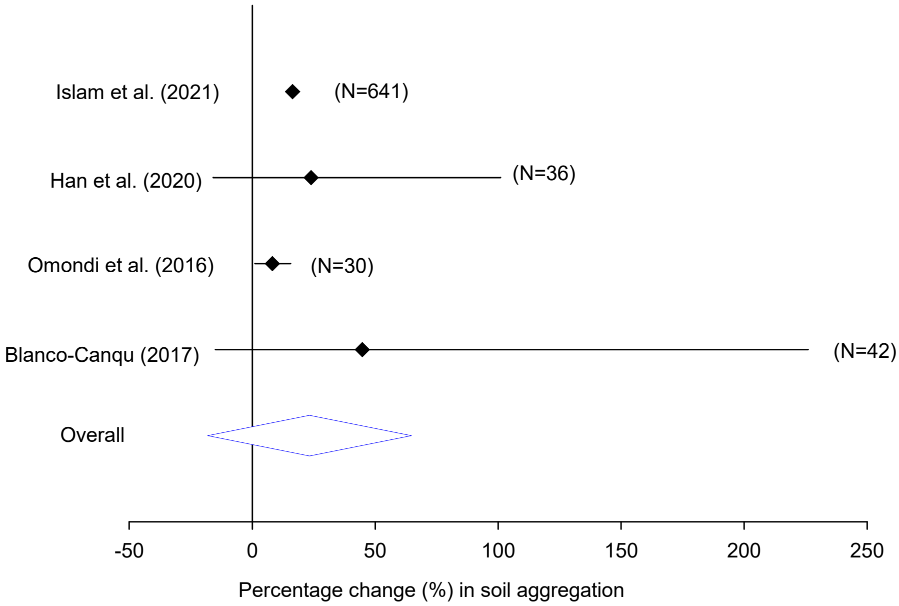

Figure S1. Changes in soil aggregation after biochar amendments. The figure is redrawn using the data from [118–121].

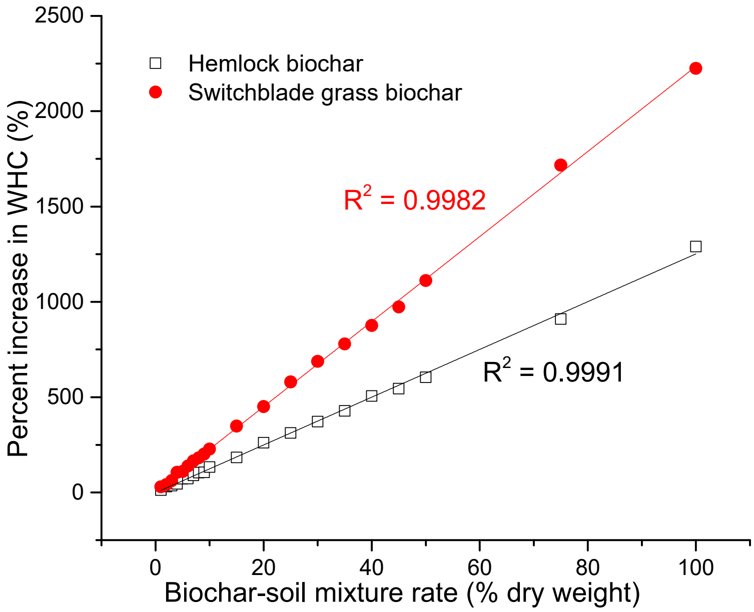

Figure S2. The relationship between increase in soil water holding capacity (WHC) and biochar application rate for a loamy sand soil. Data obtained from Table 2 of the study by Yu et al. [122].

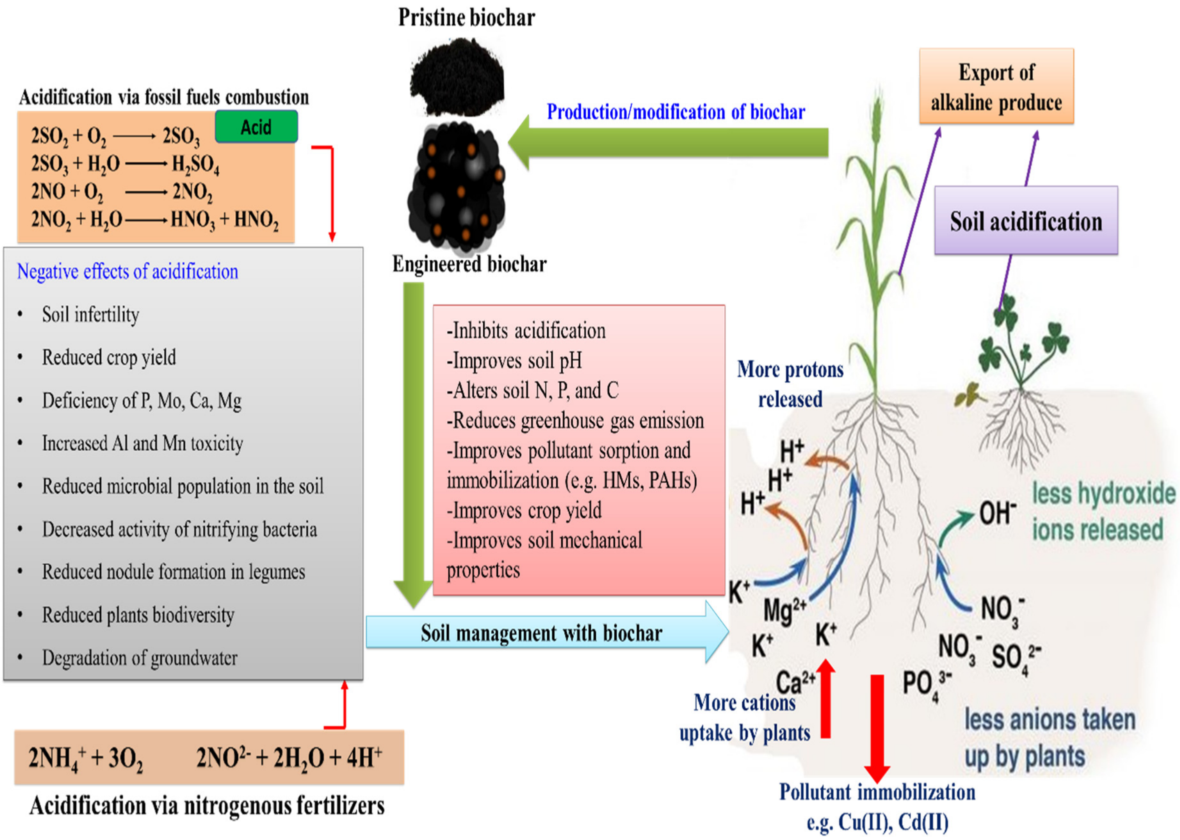

Figure S3. Schematic of biochar's role on nutrient dynamics, management of soil acidification, changes in crop performance, and pollution remediation.

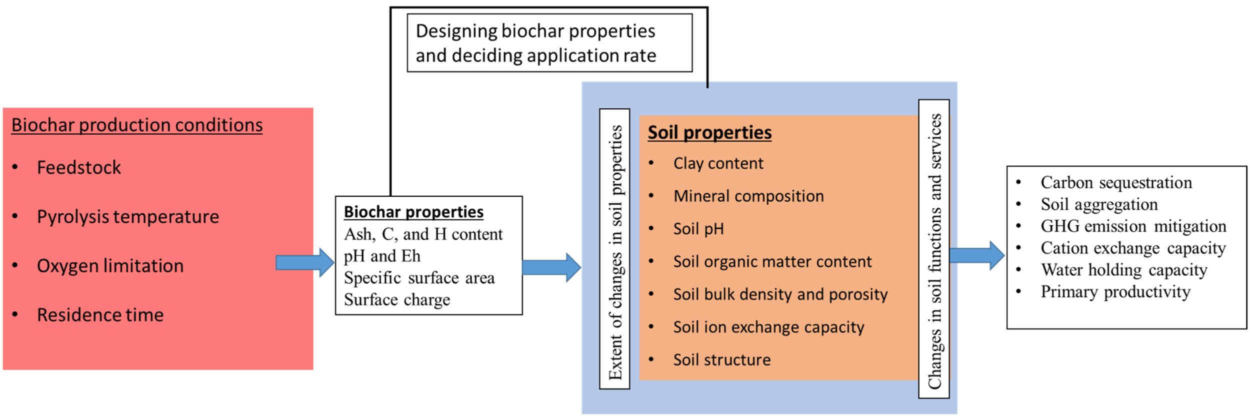

Figure S4. Guiding principles of biochar application to soil

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