Supplementary Material for

Biochar-based fertilizers and their effect on crop yield: a meta-analysis

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Table 1S – Summary of the references used in the meta-analysis

Feedstock	Pyrolysis T (°C)	Nutrient studied	Growing media*	Study type	Application Rate*	Crop type	BBF preparation method	Reference
Acacia saligna (AS)	380	NPK	Soil (Tenosol)	Field	300 kg ha^{-1}	Sorghum	Mixed thermal treatment	(Blackwell et al. 2015)
Sugarcane straw	450	PK	Oxisol	Pot	1000 kg ha^{-1}	Sugarcane	Mixed granulation	(Borges et al. 2020)
Poultry litter	500	P	Oxisol	Pot	240 mg P kg^{-1}	Grass; maize; common bean	Co-pyrolysis	(Carneiro et al. 2021)
Corn straw	500	N	Soil	Field	300 kg N ha^{-1}	Maize	Coating	(Chen et al. 2018)**
Maize straw	300; 450; 600	NP	Eutyic Cambisols	Field	450; 900; 1800 kg ha^{-1}	Maize	Co-pyrolysis, impregnation and baking	(Chen et al. 2021)
Wood biomass	450	N	Soils of different textures	Pot	6.2 g pot^{-1}	Maize	Solid mixture impregnation	(Dil et al. 2014)
Rice straw	500	NPK	Soil	Field	950 kg ha^{-1}	Rice	Coating	(Dong et al. 2019)
Rice husk	420	NP	Soil	Pot	14-17 g pot^{-1}	Japanese mustard spinach	Mixed granulation	(El Sharkawi et al. 2018)
Sugarcane filter-cake	400	NPK	Oxisol	Pot	500-2000 kg ha^{-1}	Maize	Solid mixture impregnation	(Franco et al. 2020)
NI	450	NPK	Soil	Field	NI	Peanuts	Solid mixture impregnation	(Gao et al. 2018)**
Oat hull	300	N	Soil	Pot	150 kg N ha^{-1}	Wheat	Impregnation/encapsulation	(González et al. 2015)
Vinasse	600	N	Red soil	Pot	160; 200 mg N kg^{-1}	Rapeseed	Coating	(Jia et al. 2021)
Prosopis juliflora	800	NPK; N	Soil	Field	125-250 kg ha^{-1}	Maize	Solid physical mixture	(Kamau et al. 2019)
Corn straw	500	N	Typic Haplocalcids	Pot	250 kg N ha^{-1}	Maize	Impregnation and encapsulating/coating	(Khajavi-shojaei and Moezzi 2020)
Rice straw; rice husk; rubber tree twigs	500	NPK	Oxisol	Pot	90 kg ha^{-1} N; 60 kg ha^{-1} P_2O_5; 60 kg ha^{-1} K_2O	Maize	Impregnation	(Lee et al. 2021)
Oilseed rape straws	400	N	Paddy soil	Pot	200 kg N ha^{-1}	Oilseed rape	Impregnation	(Liao et al. 2020)
Poultry litter	500	P	Oxisol	Pot	150-300 mg P kg^{-1}	Maize	Co-pyrolysis	(Lustosa Filho et al. 2019)
Poultry litter	500	P	Oxisol	Pot	200 mg P kg^{-1}	Grass	Co-pyrolysis	(Lustosa Filho et al. 2020)
Eichhornia crassipes	450	P	Sandy soil	Pot	0.3 g pot^{-1}	Maize	Nutrient-loaded adsorbent	(Mosa et al. 2018)
Poultry litter; pig manure; sewage sludge	500	P	Oxisol	Pot	200 mg P kg^{-1}	Maize	Nutrient-loaded adsorbent	(Nardis et al. 2020)
Maize straw	450	N	Alfisols	Field	1500 kg ha^{-1}	Maize	Solid physical mixture	(Peng et al. 2021)
Eucalyptus wood	350	P	Oxisol	Pot	20-120 mg P kg^{-1}	Millet	Mixed granulation/coating	(Pogorzelski et al., 2020)
Eucalyptus wood	400	N	Oxisol	Field	400; 470; 800 kg ha^{-1}	Maize	Mixed granulation	(Puga et al. 2020)

Manure compost; maize straw; municipal waste; peanut husk	450	NPK	Paddy soil	Field	450 kg ha^{-1}	Rice	Mixed granulation	(Qian et al. 2014)
Wood sawdust; sugarcane bagasse	350; 700	P	Oxisol	Pot	200-400 mg P dm^{-3}	Maize	Mixed granulation	(Santos et al. 2019)
Several biomasses	720	NPK	Several soils	Field	400 kg ha^{-1}	Maize	Impregnation	(Schmidt et al. 2017)
Green waste	550	N		Pot	2.85 g pot^{-1}	Maize	Mixed granulation	(Shi et al. 2020a)
Urban green waste	450;550	N	NI	Pot	2.85g pot^{-1}	Maize	Impregnation and encapsulating	(Shi et al. 2020b)
Cotton stalks	NI	N	Soil	Pot	NI	Cotton	Impregnation and encapsulating/coating	(Wen et al. 2017)
Wood waste	600	NP	Soil	Pot	NI	Maize	Nutrient-loaded adsorbent	(Xu et al., 2018)
Corncob	450	NPK	Sandy clay loam	Field	NI	Peanuts	-	(Xu et al., 2018)**
Spent mushroom substrate	500	NPK	Ultisols	Field	2590 kg ha^{-1}	Tea	Mixing, extruding; granulating	(Yang et al. 2021)
Wheat straw	450	NPK	Clay loam soil	Field	670 kg ha^{-1}	Green pepper	Impregnation	(Yao et al., 2015)
Wheat straw	400	NPK	Soil	Pot	NI	Wheat	Coating/Encapsulation	(Ye et al. 2019)
Corn stover	450	NPK	Soil	Field	600 kg ha^{-1}	Maize	-	(Yin et al. 2019)
Wheat straw	450	N	Soil	Pot	NI	Rice	Coating	(Yu et al. 2018)
Orchard wood	450	N	Soil	Field	NI	Wheat	Impregnation	(Zhao et al. 2016)**
Dairy manure	850	S	Potting mixture	Pot	43-171 mg S kg^{-1}	Maize	Impregnation	(Zhang et al. 2017)
Woody materials	550	N	Humic Acrisol; Mollie Gleysols	Field	1626 kg ha^{-1}	Tobacco	Impregnation and granulating	(Zhang et al. 2021)
Wheat straw	550	N	Soil	Field	1250 kg ha^{-1}	Maize	Mixed granulation	(Zheng et al. 2017)
Rice straw	450	N	Soil	Field	NI	Rice	Solid physical mixture	(Zheng et al. 2019)

NI – not informed; * as reported in the article; ** Chinese article with English abstract.

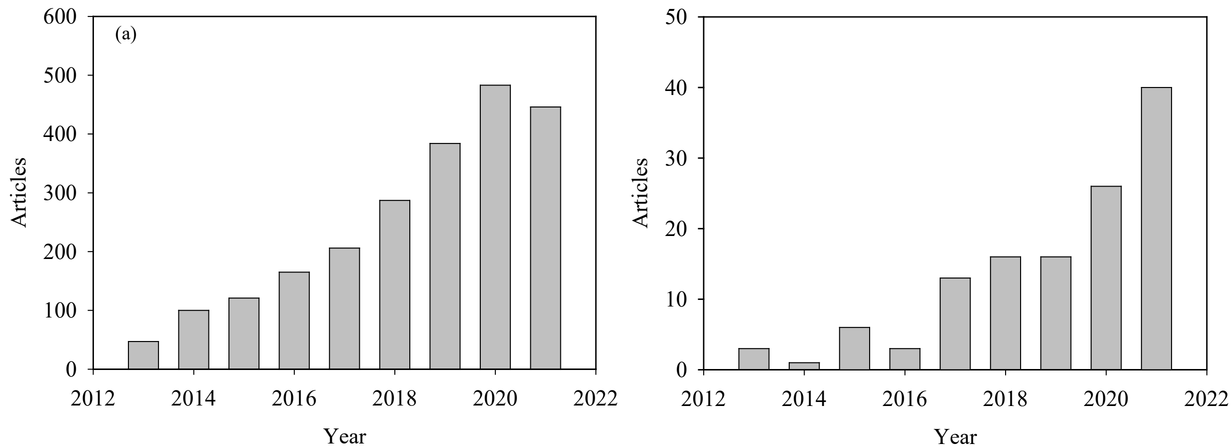


Fig. S1 – Number of published articles in recent years in the Web of Science for (a) "biochar and fertilizers" and (b) "biochar-based fertilizers". Search on September 20th 2021.

Crop productivity response of BBF versus nil control

The mean effect size of BBF compared to no fertilizer additions (nil control) was significant with a mean effect size of 210% (CI: 94-370%) (Fig. 3), while the addition of conventional fertilizers (standard control) increased crop productivity by 179% (CI: 76-342%, data not shown). In agreement with the response of crop productivity with BBF compared to the standard control (Fig. 1), in temperate climates the crop productivity response of BBF over the nil control (mean: 53%, CI: -7-150%) was not significant, while in tropical climates the response was high (mean: 143%, CI: 21-389%). Similar crop productivity increases were observed for additions of BBI to acid soils (pH ≤ 6.5) (mean: 367%, CI: 156-750%), highly-weathered soils (mean: 648%, CI: 313-1253%) and fine-textured soils (mean: 399%, CI: 184-775%). On the other hand, the crop productivity response was lower or not significant for soils with pH values > 6.5 (mean: 96%. CI: 5-263%), weakly-developed soils (mean: 66%, CI: -12-214%), other soil categories (mean: 63%, CI: -15-210%), and coarse-textured soils (mean: 95%, CI: 10-245%). All three fertilizer types (only P, only N, NPK) showed significant crop productivity increases when applied as BBF over a nil control, being largest for P (mean: 705%, CI: 443-1095%), intermediate for NPK (mean:

342%, CI: 191-573%) and lowest for N (mean: 120%, CI: 38-252%). No significant differences between granular (mean: 164%, CI: 69-313%) and powder BBF (mean: 206%, CI: 97-373%) were observed. Large and significant crop productivity responses were found for pot experiments (mean: 329%, CI: 153-630%), with no significant crop productivity response for field experiments (mean: 72%, CI: -12-236%). Nutrient-poor biochars in BBF had a lower effect on crop productivity (mean: 129%, CI: 38-279%) than nutrient-rich biochars (mean: 461%, CI: 164-1094%). For biochar HHT, all three categories showed a significant crop productivity increase, but no specific trend could be distinguished between them. Crop productivity responses with BBF were significant and similar for biochars with ≤ 30% C (mean: 202%, CI: 86-391%) and > 30% C (mean: 240%, CI:108-453%).

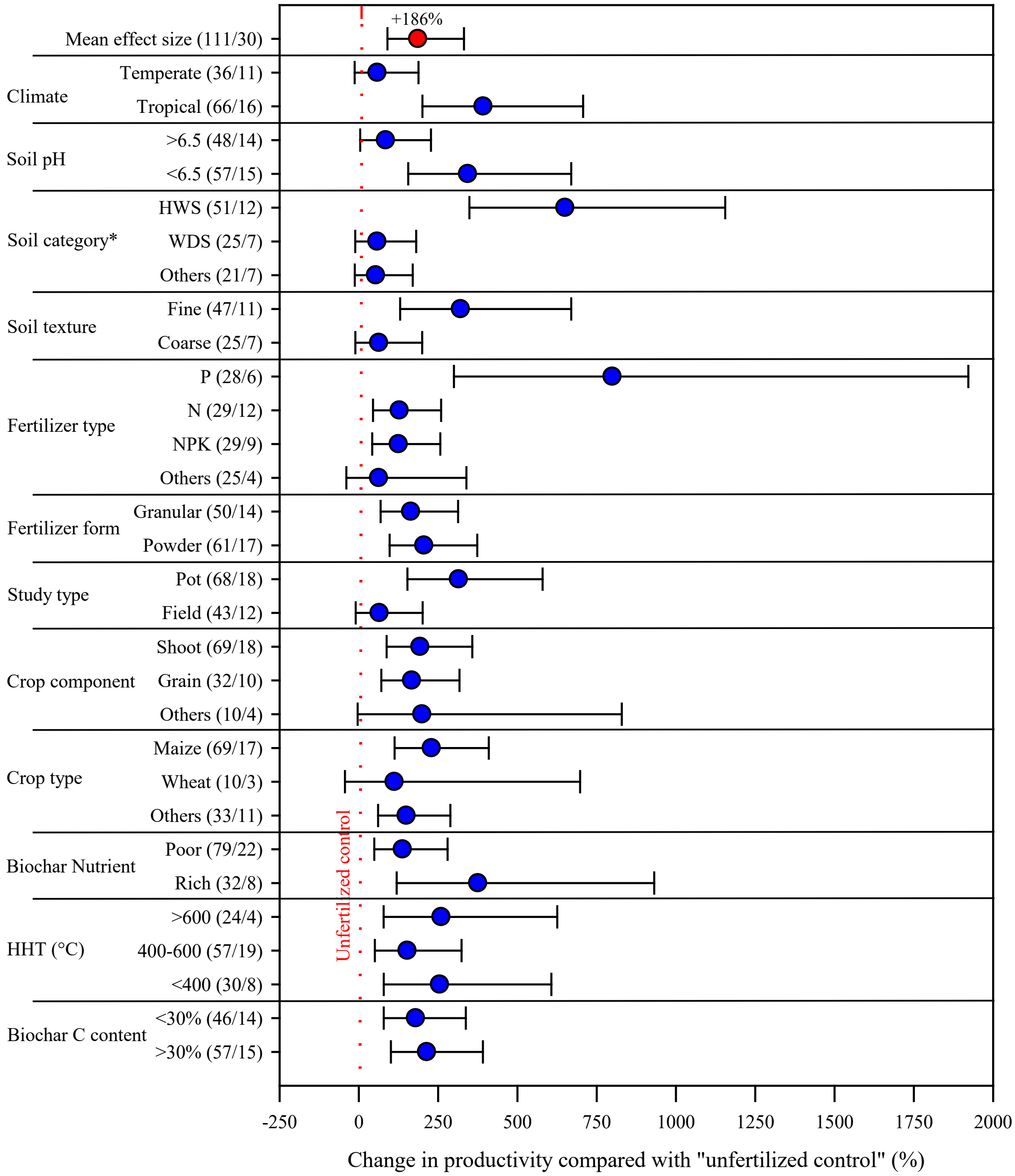


Fig. S2. Change in crop productivity as a result of additions of biochar-based fertilizers (BBF) in comparison with the unfertilized control (red dotted line). The comparison is for the grand mean effect size and for several categories related to the climate, soil characteristics and fertilizer characteristics. The circles represent the mean value and the bars represent the 95% confidence interval. The difference is considered significant ($p < 0.05$) from the unfertilized control when the bars do not overlap with the dotted line. Sub-categories were considered to differ between them when their 95% confidence intervals did not overlap. The numbers in parenthesis represent the number of pairwise comparisons (on the left)/number of independent studies (on the right) from which the comparisons were made. * Soil categories were divided in highly-weathered soils (HWS), weakly-developed soils (WDS) and “others”.

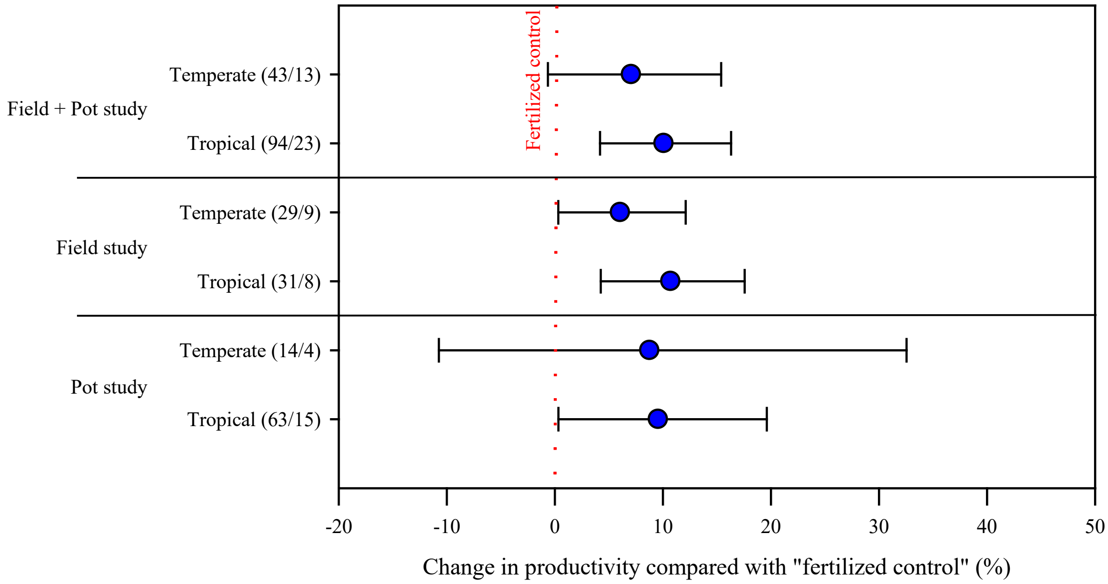
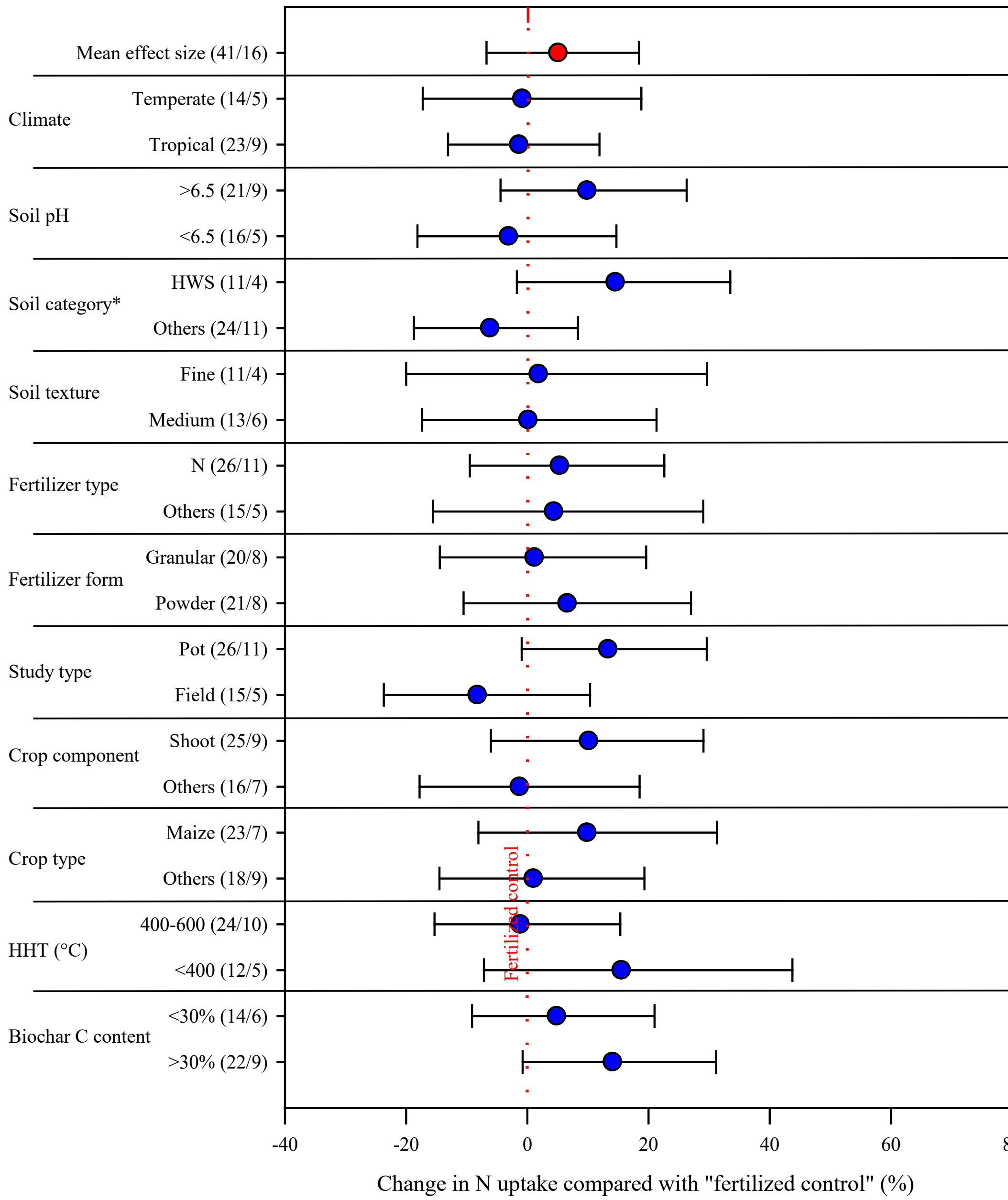
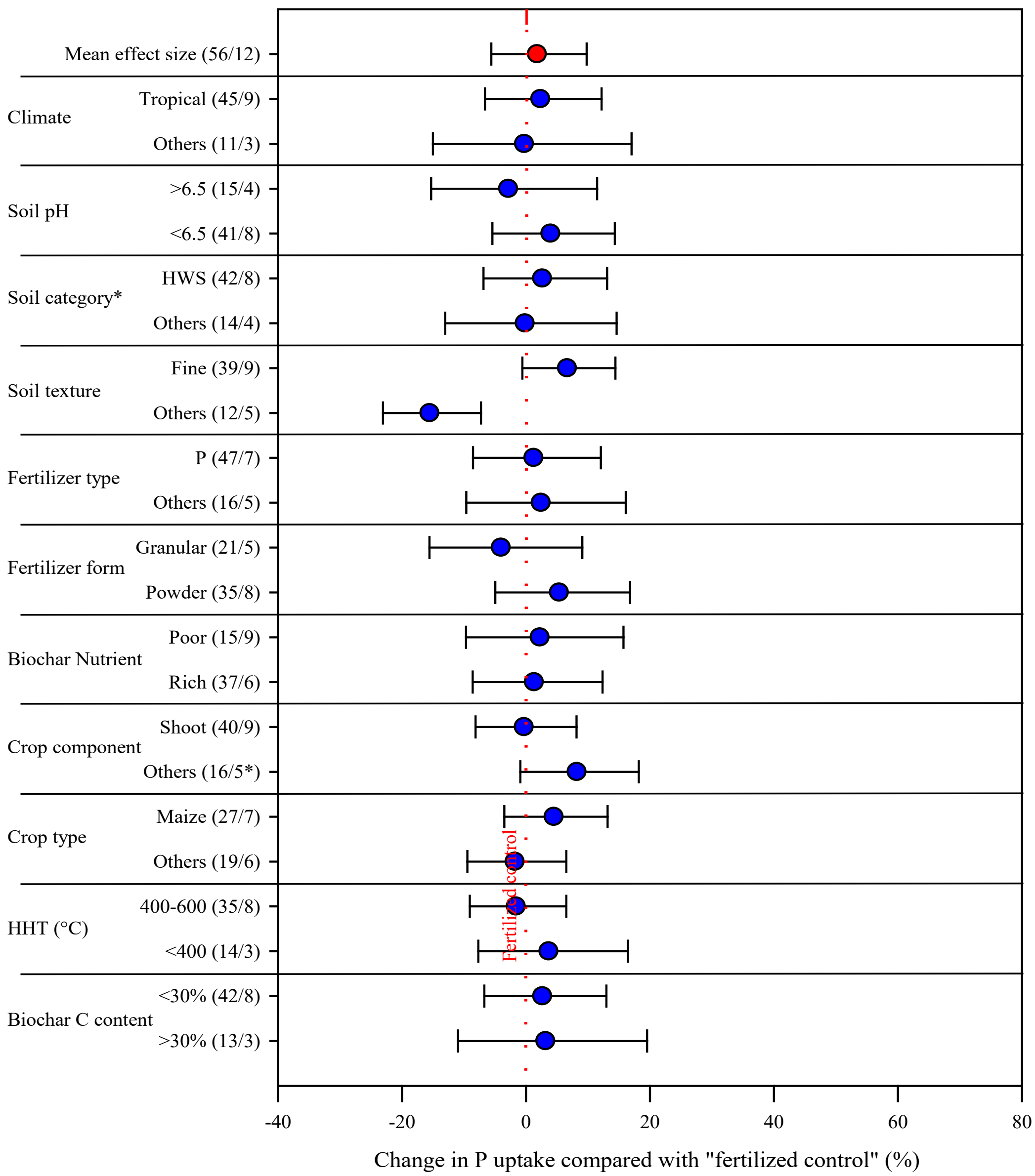


Fig. S3. Change in crop productivity as a result of additions of biochar-based fertilizers (BBF) in comparison with the fertilized control (red dotted line). The comparison is for both combined and separate analysis for pot and field studies. The circles represent the mean value and the bars represent the 95% confidence interval. The difference is considered significant ($p < 0.05$) from the fertilized control when the bars do not overlap with the dotted line. The numbers in parenthesis represent the number of pairwise comparisons (on the left)/number of independent studies (on the right) from which the comparisons were made.


Mean effect size (41/16)
Climate
Temperate (14/5)
Tropical (23/9)
Soil pH
>6.5 (21/9)
<6.5 (16/5)
Soil category*
HWS (11/4)
Others (24/11)
Soil texture
Fine (11/4)
Medium (13/6)
Fertilizer type
N (26/11)
Others (15/5)
Fertilizer form
Granular (20/8)
Powder (21/8)
Study type
Pot (26/11)
Field (15/5)
Crop component
Shoot (25/9)
Others (16/7)
Crop type
Maize (23/7)
Others (18/9)
HHT (°C)
400-600 (24/10)
<400 (12/5)
Biochar C content
<30% (14/6)
>30% (22/9)
Fertilized control
-40
-20
0
20
40
60
80
Change in N uptake compared with "fertilized control" (%)



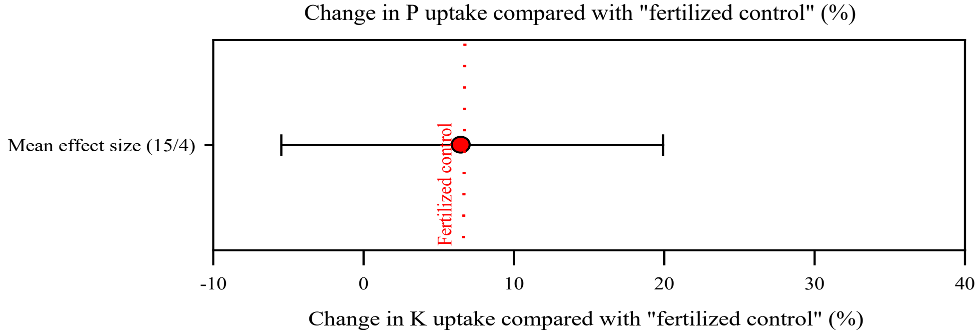


Fig. S4 – Change in nutrient uptake (N, P and K) as a result of additions of biochar-based fertilizers (BBF) in comparison with the standard control (red dotted line). The comparison is for the grand mean effect size and for several categories related to climate, soil and fertilizer characteristics. The circles represent the mean value and the bars represent the 95% confidence interval. The difference is considered significant ($p<0.05$) from the standard control when the bars do not overlap with the dotted line. The numbers in parenthesis represent the number of pairwise comparisons (on the left)/ number of independent studies (on the right) from which the comparisons were made. This dataset is the same of Fig. 4 regarding crop nutrient uptake.

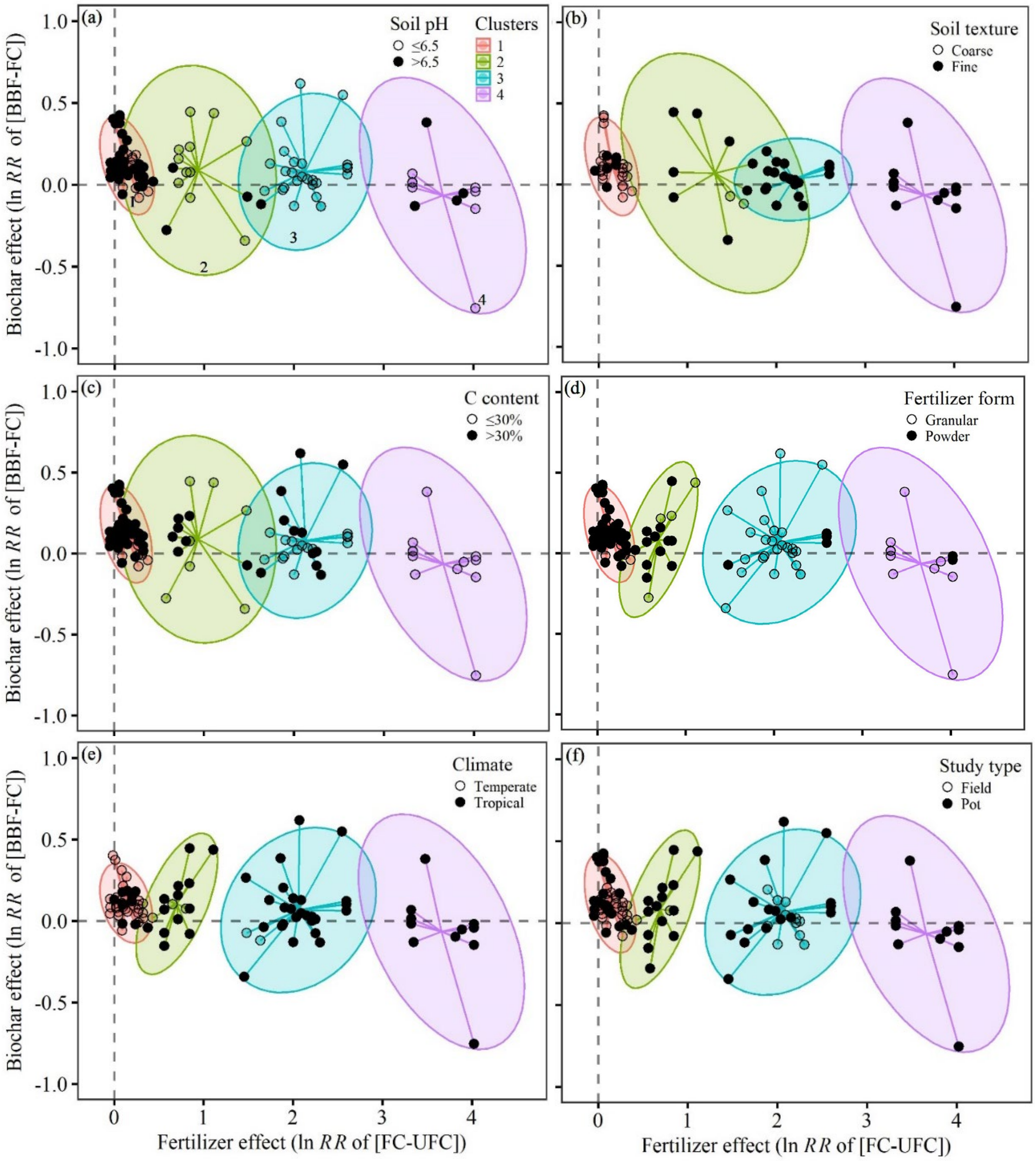


Fig. S5 - Detailed cluster of crop yield response of standard control (FC) minus nil control (UFC) (x-axis) and biochar-based fertilizer (BBF) minus standard control (FC) (y-axis) categorized by soil pH (< 6.5 or ≥ 6.5); soil texture (coarse or fine); carbon content (< 30% or > 30%); fertilizer form (granular or powder); climate (temperate of tropical); and study type (field or pot).

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