agronomy

MDPI

*Article*

# Biochar-Ca and Biochar-Al/-Fe mediated phosphate exchange capacity are main drivers of the different biochar effects on plants in acidic and alkaline soils

**Supplementary Materials**

**Table S1.** Analysis of soil used in Growth Chamber experiment

| Parameter | Value | Units |
|---|---|---|
| **pH $H_2O$** | 8.30 | |
| **Organic Matter** | 2.98 | g $100g^{-1}$ |
| **Total Nitrogen** | 0.11 | g $100g^{-1}$ |
| **C/N Ratio** | 15.7 | - |
| **Available P** | 64.5 | mg $kg^{-1}$ |
| **Carbonates** | 8.09 | g $100g^{-1}$ |
| **Electric Conductivity 1:1(p/v)** | 0.43 | dS $m^{-1}$ |
| **Sand** | 409 | g $kg^{-1}$ |
| **Loam** | 382 | g $kg^{-1}$ |
| **Clay** | 209 | g $kg^{-1}$ |
| **Cation Exchange Capacity** | 28.1 | cmol(+) $kg^{-1}$ |
| **Exchangeable Ca** | 26.4 | cmol(+) $kg^{-1}$ |
| **Exchangeable Mg** | 0.82 | cmol(+) $kg^{-1}$ |
| **Exchangeable K** | 0.63 | cmol(+) $kg^{-1}$ |
| **Exchangeable Na** | 0.26 | cmol(+) $kg^{-1}$ |
| **DTPA extractable Fe** | 56.6 | mg $kg^{-1}$ |
| **DTPA extractable Cu** | 0.85 | mg $kg^{-1}$ |
| **DTPA extractable Mn** | 4.49 | mg $kg^{-1}$ |
| **DTPA extractable Zn** | 1.43 | mg $kg^{-1}$ |

**Table S2.** Analysis of acidic soil used in Greenhouse experiment

| Parameter | Value | Units |
|---|---|---|
| **pH $H_2O$** | 5.30 | |
| **Organic Matter** | 2.01 | g $100g^{-1}$ |
| **Total Nitrogen** | 0.25 | g $100g^{-1}$ |
| **C/N Ratio** | 8.20 | - |
| **Available P** | 14.9 | mg $kg^{-1}$ |
| **Carbonates** | 0.60 | g $100g^{-1}$ |
| **Electric Conductivity 1:1(p/v)** | 0.02 | dS $m^{-1}$ |
| **Sand** | 150 | g $kg^{-1}$ |
| **Silt** | 440 | g $kg^{-1}$ |
| **Clay** | 410 | g $kg^{-1}$ |
| **Cation Exchange Capacity** | 28.1 | cmol(+) $kg^{-1}$ |
| **Exchangeable Ca** | 1.60 | cmol(+) $kg^{-1}$ |
| **Exchangeable Mg** | 0.51 | cmol(+) $kg^{-1}$ |
| **Exchangeable K** | 0.81 | cmol(+) $kg^{-1}$ |
| **Exchangeable Na** | 0.02 | cmol(+) $kg^{-1}$ |
| **Available Fe** | 165 | mg $kg^{-1}$ |
| **Available Cu** | 11.3 | mg $kg^{-1}$ |
| **Available Mn** | 27.9 | mg $kg^{-1}$ |
| **Available Zn** | 5.75 | mg $kg^{-1}$ |

**Table S3.** Analysis of alkaline soil used in Greenhouse experiment

| Parameter | Value | Units |
|---|---|---|
| **pH $H_2O$** | 8.20 | |
| **Organic Matter** | 1.81 | g $100g^{-1}$ |
| **Total Nitrogen** | 0.21 | g $100g^{-1}$ |
| **C/N Ratio** | 8.62 | - |
| **Available P** | 23.1 | mg $kg^{-1}$ |
| **Carbonates** | 21.4 | g $100g^{-1}$ |
| **Electric Conductivity 1:1(p/v)** | 0.22 | dS $m^{-1}$ |
| **Sand** | 210 | g $kg^{-1}$ |
| **Silt** | 420 | g $kg^{-1}$ |
| **Clay** | 370 | g $kg^{-1}$ |
| **Cation Exchange Capacity** | 27.0 | cmol(+) $kg^{-1}$ |
| **Exchangeable Ca** | 18.5 | cmol(+) $kg^{-1}$ |
| **Exchangeable Mg** | 2.67 | cmol(+) $kg^{-1}$ |
| **Exchangeable K** | 5.03 | cmol(+) $kg^{-1}$ |
| **Exchangeable Na** | 0.81 | cmol(+) $kg^{-1}$ |
| **Available Fe** | 23.6 | mg $kg^{-1}$ |
| **Available Cu** | 9.28 | mg $kg^{-1}$ |
| **Available Mn** | 17.5 | mg $kg^{-1}$ |
| **Available Zn** | 6.91 | mg $kg^{-1}$ |

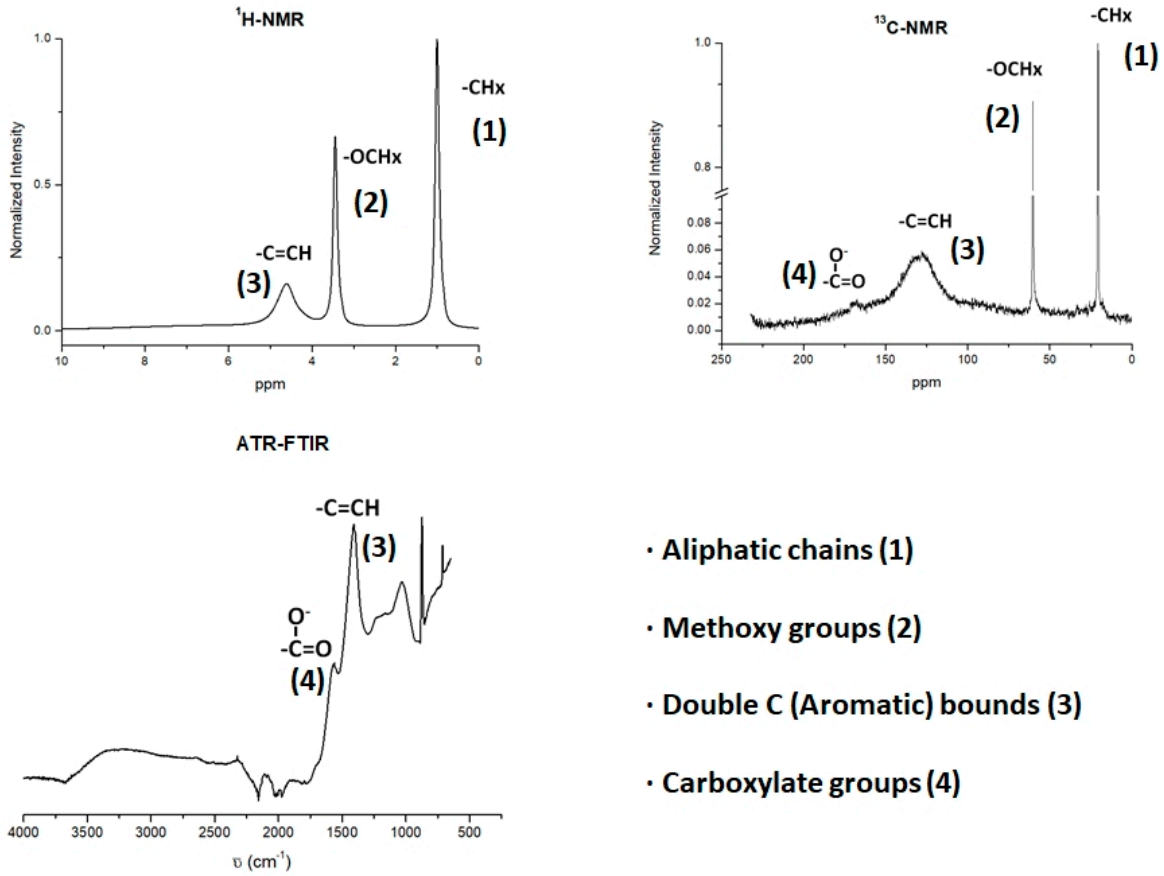


**Figure S1:** 1H-, 13C-NMR and ATR-FTIR spectra. Structural groups are indicated in brackets and in the different spectra.

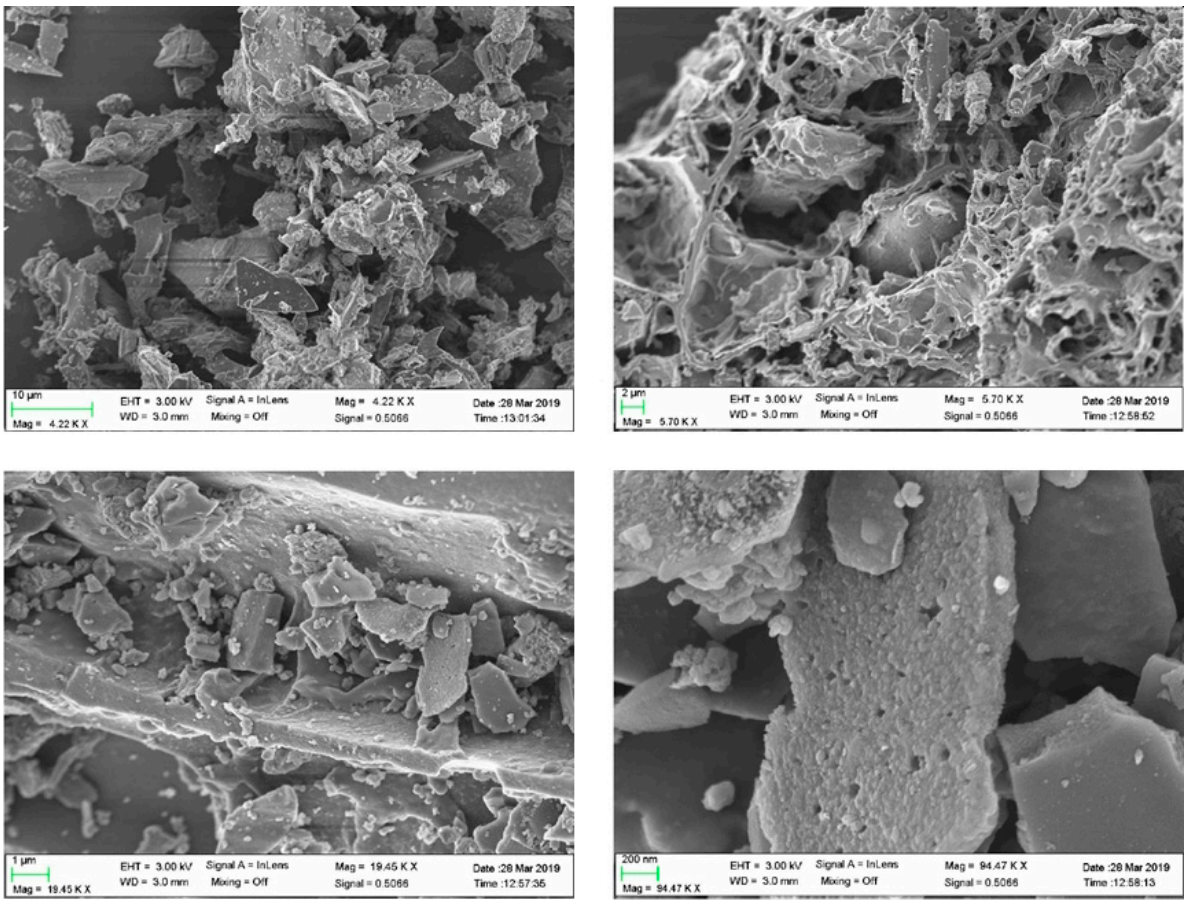


**Figure S2:** SEM images of biochar. Scale bars and magnificence are indicated in the images.


**Figure S3:** Biochar fertilizer manual manufacturing in rotatory dish.

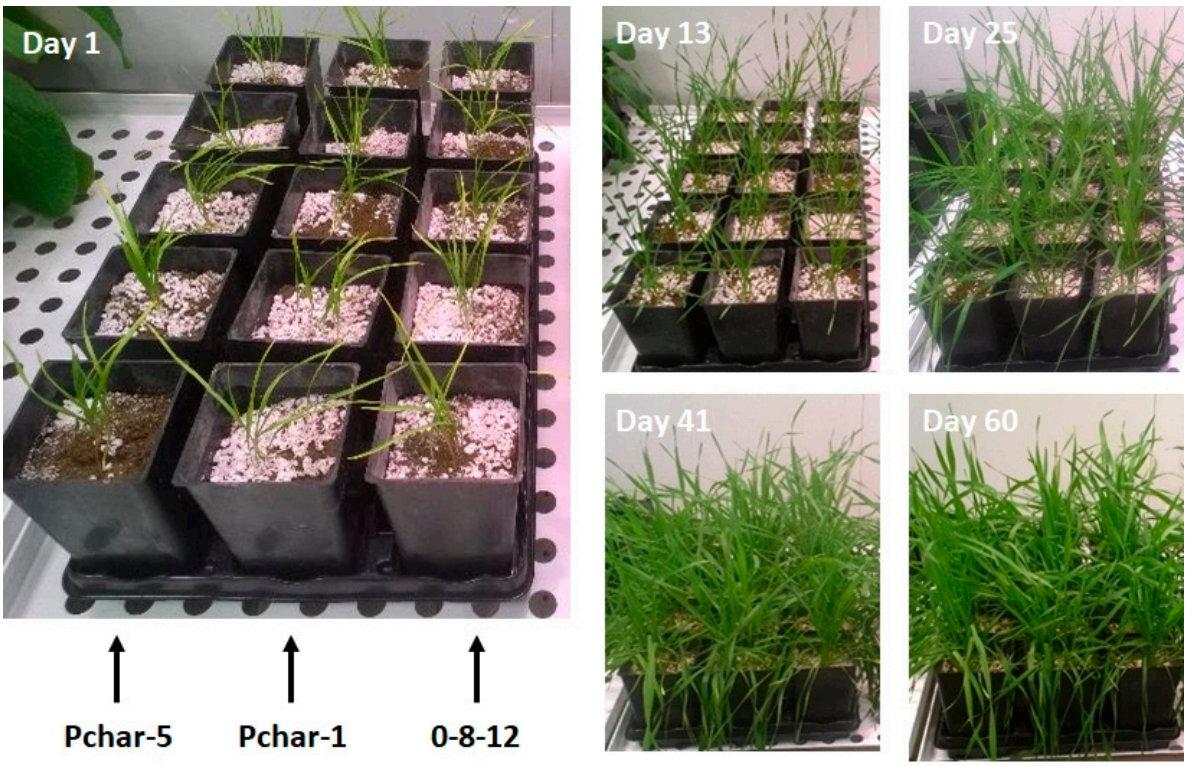


**Figure S4:** Growth Chamber experiment in Wheat plants using biochar-based fertilizer.

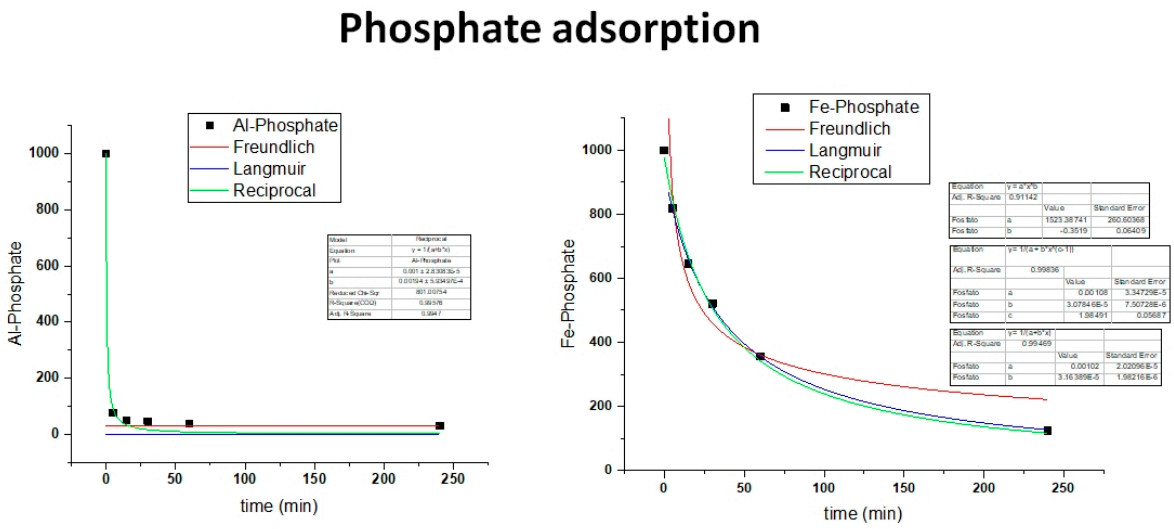


**Figure S5:** Mathematical models for Pi-Al-biochar and Pi-Fe-biochar adsorption isotherms.

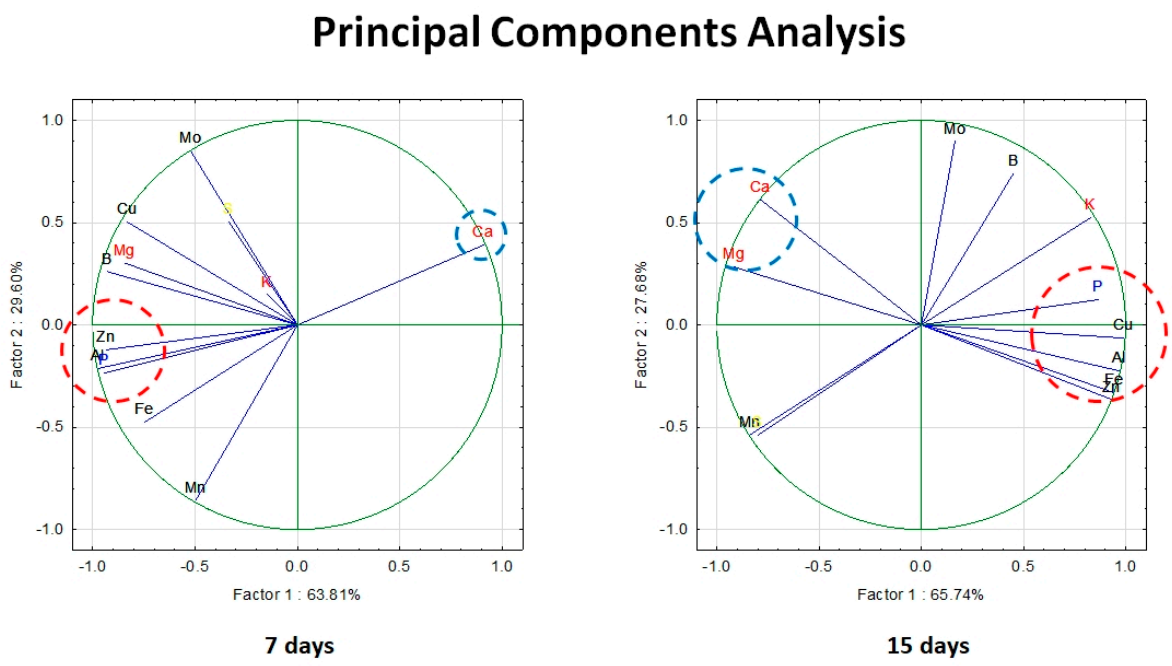


**Figure S6:** PCA for biochar-soil interactions at 7 and 15 days.


**Figure S7:** Greenhouse experiment in Tomato plants in both acidic and alkaline soils. Left column experiment in acidic soil, from top to bottom evolution in time. Right column experiment in alkaline soil, from top to bottom evolution in time. Replications of all treatments were randomness located in each soil to avoid differences by localization

## Acidic soil

| mg kg$^{-1}$ | | Control - | Control + | Biochar | | Control - | Control + | Biochar |
|---|---|---|---|---|---|---|---|---|
| mean | Al | 296 | 134 | 97.8 | Mn | 201 | 381 | 207 |
| S.D. | | 43.8 | 57.4 | 44.6 | | 45.5 | 78.6 | 24.7 |
| | B | 23.6 | 16.7 | 34.6 | Mo | 0.67 | 0.25 | 0.21 |
| | | 8.35 | 1.54 | 3.55 | | 0.29 | 0.00 | 0.09 |
| | Ca | 21991 | 20252 | 30832 | Na | 596 | 359 | 266 |
| | | 44.9 | 1017 | 2340 | | 38.1 | 199 | 71.2 |
| | Cu | 13.9 | 19.8 | 16.1 | P | 525 | 819 | 834 |
| | | 5.08 | 1.97 | 1.34 | | 107 | 77.9 | 45.7 |
| | Fe | 268 | 165 | 137 | S | 3462 | 2250 | 2701 |
| | | 40.1 | 51.6 | 34.0 | | 204 | 179 | 213 |
| | K | 26922 | 27385 | 26323 | Si | 124 | 72.0 | 139 |
| | | 3764 | 4408 | 2911 | | 69.0 | 27.8 | 24.8 |
| | Mg | 1539 | 991 | 972 | Zn | 74.8 | 37.0 | 34.0 |
| | | 502 | 123 | 159 | | 23.4 | 8.04 | 6.90 |

## Alkaline soil

| mg kg$^{-1}$ | | Control - | Control + | Biochar | | Control - | Control + | Biochar |
|---|---|---|---|---|---|---|---|---|
| mean | Al | 83.2 | 49.7 | 60.5 | Mn | 112 | 52.1 | 57.5 |
| S.D. | | 22.6 | 18.5 | 17.7 | | 33.4 | 8.83 | 10.0 |
| | B | 27.3 | 31.2 | 36.4 | Mo | 1.97 | 2.62 | 2.80 |
| | | 8.46 | 3.48 | 3.18 | | 1.76 | 0.38 | 0.21 |
| | Ca | 49453 | 50746 | 51925 | Na | 512 | 344 | 368 |
| | | 883 | 1406 | 1711 | | 61.7 | 25.1 | 12.0 |
| | Cu | 15.6 | 12.9 | 11.6 | P | 1127 | 2221 | 2454 |
| | | 2.80 | 1.17 | 2.19 | | 182 | 268 | 410 |
| | Fe | 149 | 165 | 153 | S | 4119 | 3097 | 3859 |
| | | 0.15 | 29.0 | 26.0 | | 11.5 | 143 | 468 |
| | K | 32160 | 30398 | 35320 | Si | 71.8 | 88.0 | 116 |
| | | 5843 | 3067 | 3647 | | 13.4 | 14.3 | 20.6 |
| | Mg | 4207 | 3356 | 3673 | Zn | 52.5 | 37.1 | 37.3 |
| | | 424 | 268 | 454 | | 15.6 | 8.14 | 4.92 |

**Figure S8:** Nutrient foliar content in Tomato plants in both acidic and alkaline soils.