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Research article

Effect of biochars produced from solid organic municipal waste on soil quality parameters

P. Randolph [a], R.R. Bansode [a], O.A. Hassan [a], Dj. Rehrah [b], R. Ravella [c], M.R. Reddy [c], D.W. Watts [d], J.M. Novak [d], M. Ahmedna [b, *]

[a] *Center for Excellence in Post-Harvest Technologies, North Carolina Agricultural and Technical State University, North Carolina Research Campus, Kannapolis, NC, 28081, USA*
[b] *College of Health Sciences, Qatar University, P.O. Box 2713, Doha, Qatar*
[c] *The Department of Natural Resources and Environmental Design, North Carolina Agricultural and Technical State University, Greensboro, NC, 27411, USA*
[d] *USDA-ARS, Coastal Plains Research Center, 2611 West Lucas Street, Florence, SC, 29501, USA*

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ABSTRACT

New value-added uses for solid municipal waste are needed for environmental and economic sustainability. Fortunately, value-added biochars can be produced from mixed solid waste, thereby addressing solid waste management issues, and enabling long-term carbon sequestration. We hypothesize that soil deficiencies can be remedied by the application of municipal waste-based biochars. Select municipal organic wastes (newspaper, cardboard, woodchips and landscaping residues) individually or in a 25% blend of all four waste streams were used as feedstocks of biochars. Three sets of pyrolysis temperatures (350, 500, and 750 °C) and 3 sets of pyrolysis residence time (2, 4 and 6 h) were used for biochar preparation.

The biochar yield was in the range of 21–62% across all feedstocks and pyrolysis conditions. We observed variations in key biochar properties such as pH, electrical conductivity, bulk density and surface area depending on the feedstocks and production conditions. Biochar increased soil pH and improved its electrical conductivity, aggregate stability, water retention and micronutrient contents. Similarly, leachate from the soil amended with biochar showed increased pH and electrical conductivity. Some elements such as Ca and Mg decreased while NO_3-N increased in the leachates of soils incubated with biochars. Overall, solid waste-based biochar produced significant improvements to soil fertility parameters indicating that solid municipal wastes hold promising potential as feedstocks for manufacturing value-added biochars with varied physicochemical characteristics, allowing them to not only serve the needs for solid waste management and greenhouse gas mitigation, but also as a resource for improving the quality of depleted soils.

1. Introduction

Food, agricultural, and landscaping by-products and other solid municipal waste products (newspapers, packaging, furniture woods, wood from building demolition, etc.) are common municipal solid waste streams that are traditionally placed in landfills, which is an unsustainable and environmentally unsound practice. Globally, agricultural soils have significant deficiencies in a host of essential trace elements and macro-nutrients; and these deficiencies can affect the nutritional quality of edible crops with direct consequences for human health (Alloway, 2008; Roberts et al., 2015). On the other hand, agricultural soil contains 230 times more carbon than that which is emitted by anthropogenic activities, thus accounting for the largest carbon pool on earth (Sommer and Bossio, 2014).

Fortunately, these challenges can be mitigated by producing biochars from mixed organic solid waste from municipalities and agricultural and landscaping operations, and using them as soil enhancements and long-term carbon sequestration. Recent studies have suggested that the soil amended with biochar can potentially enhance agronomic productivity (Spokas et al., 2012; Steinbeiss et al., 2009; Akhtar et al., 2014). The traditional solid waste disposal methods such as landfill and composting, generate greenhouse gases that contribute to climate change. In contrast,

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* Corresponding author.
E-mail address: ahmedna@qu.edu.qa (M. Ahmedna).

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biochars are capable of fertilizing soil while sequestering carbon and reducing the emission of greenhouse gases that are typically released from decaying organic matter (Cooper et al., 2011).

Depending on feedstock and pyrolysis conditions, biochars also tend to have the most favorable effects on acidic and neutral soils. Therefore, this liming effect of biochar is an important mechanism in increasing plant productivity (Jeffery et al., 2011; Roberts et al., 2015). Hence, the value-added use of solid waste generated by municipalities as feedstocks of biochars may provide both economic and environmental benefits.

The slow degradation of biochar enhances soil properties by increasing soil organic carbon (SOC), water-holding capacity, and cation exchange capacity (CEC) (Yanai et al., 2007). This allows nutrients to be retained for plant uptake, and limits the infiltration of chemical fertilizers and pesticides (Schulz and Glaser, 2012; Yang et al., 2010). These applications make solid municipal waste a promising resource to produce value-added biochars with varied physicochemical characteristics. Such biochars could potentially serve not only as an alternative to bio-waste management and greenhouse gas mitigation, but also as means to improve depleted soil. However, one of the potential limitations of solid municipal waste as a feedstock for biochar is that they may add contaminants, if not properly sorted (Devi and Saroha, 2014). The most common contaminants are heavy metals and poly aromatic hydrocarbons (Oleszczuk et al., 2013). While most biochars prepared from agricultural byproducts are considered to sorb heavy metals in soil, the adsorption properties greatly depend on the source and heterogeneity of the feedstock. For example, biochars prepared from some unsorted wastes and sewage sludge may contain greater percentage of heavy metals and could lead to soil contamination. (Lu et al., 2016). Likewise, polyaromatic hydrocarbons (PAHs) can be formed during pyrolysis of biomass and could constitute significant source of contamination in soil (Fabbri et al., 2013). Hence, these sources of solid waste are less attractive than sortable solid waste materials such as paper, demolition wood, landscaping residues, and food waste.

We hypothesize that soil properties can be improved with biochars from the above sortable solid waste stream. Therefore, this study was conducted to: (1) develop biochars from solid municipal waste (newspaper, cardboard, woodchips and plant residues) and (2) determine how feedstock and pyrolysis conditions affect the properties of the soil amended with these biochars.

2. Materials and methods

2.1. Preparation and characterization of biochars

Select solid municipal waste (newspaper, cardboard, woodchips and landscaping residues) were used individually or in a 25% (w/w) blend of each as a feedstock for biochar preparation. These residues were chosen due to their commonality in municipal solid waste. A 5 × 3 × 3 factorial design (Table 1.) consisting of 5 different agricultural feedstocks, 3 pyrolysis temperatures (350, 500, and 700 °C) and 3 pyrolysis residence times (2, 4 and 6 h). Newspaper and cardboard were shredded using an industry-grade shredder and blended into pulp. Woodchips, plant residues from landscaping and blends were oven-dried at 60 °C overnight and pyrolyzed using a Lindberg furnace as described by Rehrah et al., 2014. Biochar properties such as mass yield, pH, electrical conductivity (EC), bulk density and total surface area were measured using methods described previously (Rehrah et al., 2014).

Table 1
Production Conditions for solid waste-based biochars.

Feedstock	Pyrolysis Temperature (°C)	Pyrolysis time (Hrs)		
Woodchips	350	2	4	6
	500	2	4	6
	700	2	4	6
Newspaper	350	2	4	6
	500	2	4	6
	700	2	4	6
Cardboard	350	2	4	6
	500	2	4	6
	700	2	4	6
Plant residues[a]	350	2	4	6
	500	2	4	6
	700	2	4	6
Blends[b]	350	2	4	6
	500	2	4	6
	700	2	4	6

[a] Plant residues from landscaping and agricultural operations.
[b] 25% blend of 4 feedstocks.

2.2. Soil and biochar incubation

Bulk samples of the Enon fine sandy clay loam soils from the Ap horizon (0–15 cm deep) was used in this study. The soil was air dried, 2-mm sieved, and stored for use in the incubation experiments. The Enon soil was then placed in open-top greenhouse pots (8.5 cm diameter and 13 cm tall). A Box-Behnken experimental design was used to decrease the number of treatments to a manageable level (150 treatments) with three replications at the center. To mimic the field conditions, pots containing 500 g soil with added biochars at 0, 0.5, 1, or 2%; wt/wt and maintained at 10–12% (wt/wt) moisture were incubated in a greenhouse at temperatures 18–29 °C and relative humidity 35–75% for 120 days as described by Novak et al., 2009.

2.2.1. Soil fertility parameters analysis

After 120 days of incubation, the different biochar-treated soils were removed from pots and air-dried for 2–3 days and sieved (2-mm mesh sieve). Fifteen grams of soil was mixed thoroughly in 15 mL of deionized water and was allowed to stand for 1 h. The pH of the solution was measured using a pH meter (Isaac, 1983; Donohue, 1992). Mehlich I extractable soil nutrients (Ca, K, Mg and P) were analyzed by Clemson University-Agricultural Services Laboratory (Clemson, SC). Aggregate stability of the soil was conducted using a method described by Sainju et al., 2003.

2.3. Soil leaching and leachates analysis

Soil leachates that were collected during the incubation period were filtered using a 0.45 μm membrane. Ten milliliters of filtered leachate was used for analysis of pH and EC using pH meter (Oakton Instruments, Vernon Hills, IL) and EC meter, respectively (Spectrum Technologies Inc., Aurora, IL). The amount of water retained in soil was calculated as follows:

$$Water\ retention\ (mL/g) = \frac{Vol.\ of\ water\ added\ to\ the\ pot\ (mL) - Vol.\ of\ water\ drained\ (mL)}{Weight\ of\ the\ soil\ in\ the\ pot\ (g)} \quad (1)$$

An aliquot of filtered leachates was acidified with concentrated HNO_3 (2%, v/v). The aliquot was subjected to ICP elemental analysis as described by Novak et al., 2009.

3. Results

3.1. Physico-chemical properties of biochars

Data obtained indicate that biochar yield/recovery decreases as pyrolysis temperature increases, especially with longer pyrolysis time (Fig. 1). Pyrolysis of all feedstocks at 350 °C for 2 h yielded the highest recovery of biochar. Bulk density was highest in biochar prepared from wood chips and plant residues (0.2 g/mL), most likely due to the high lignin content of wood (Fig. 2A). Softer materials, like newspaper and cardboard, generally yielded chars with a low bulk density due to their low lignin content and lack of tight packing of material during pyrolysis. The total surface area (TSA) increased drastically with increases in pyrolysis temperature, reaching a maximum of 298.2 ± 2.9 m^2/g in the woodchip-based biochar produced at 700 °C (Fig. 2B). This can be explained by pore and crevice formation in the carbon lattice as it condenses and increases with temperatures following volatilization of non-carbon components (Zhang et al., 2015). The combination of high temperature and short residence duration seems to produce biochars

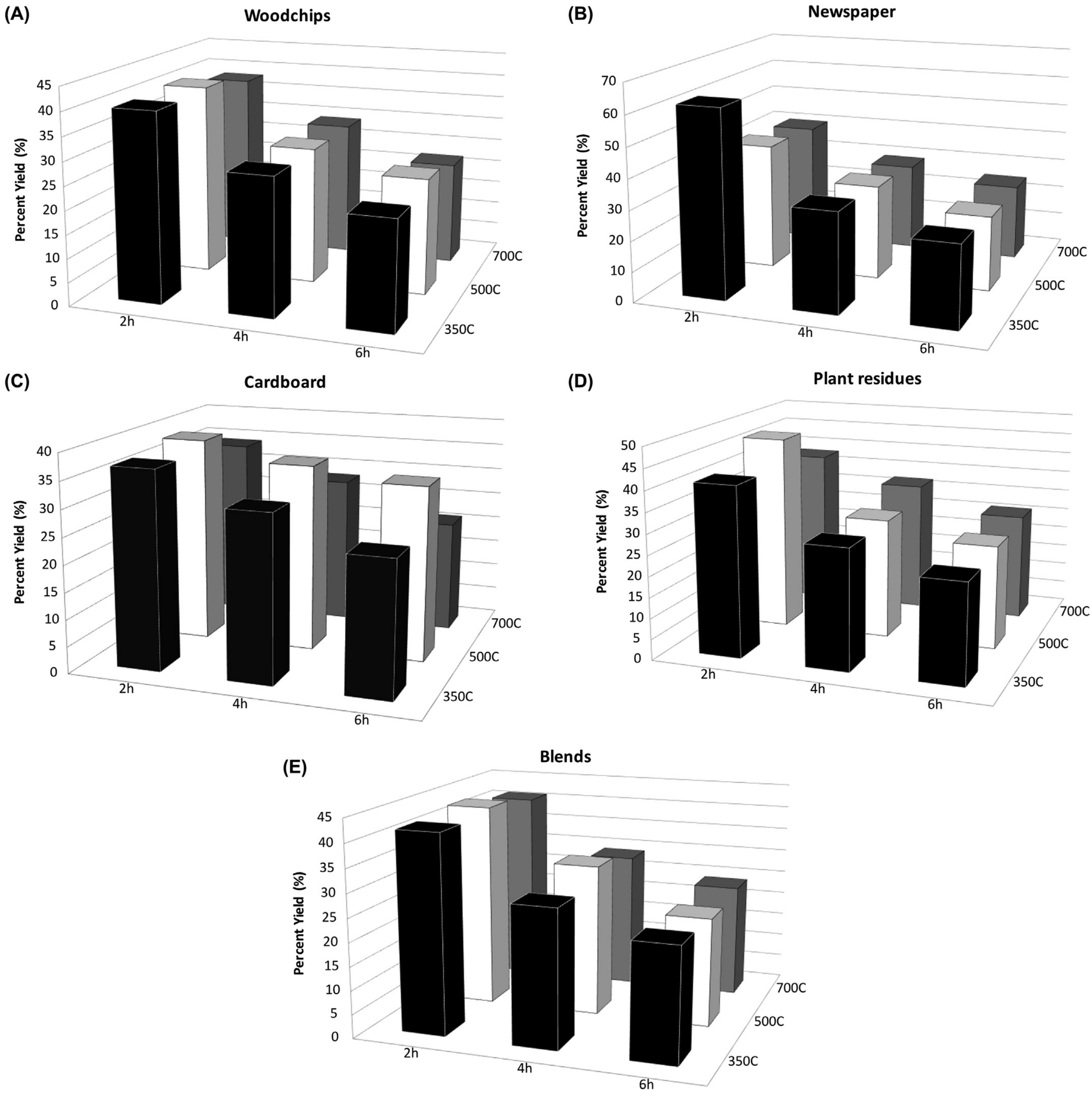

Fig. 1. Percent mass yield of biochars from solid municipal waste: (A) Woodchips; (B) Newspaper; (C) Cardboard; (D) Plant residues; and (E) Blends.

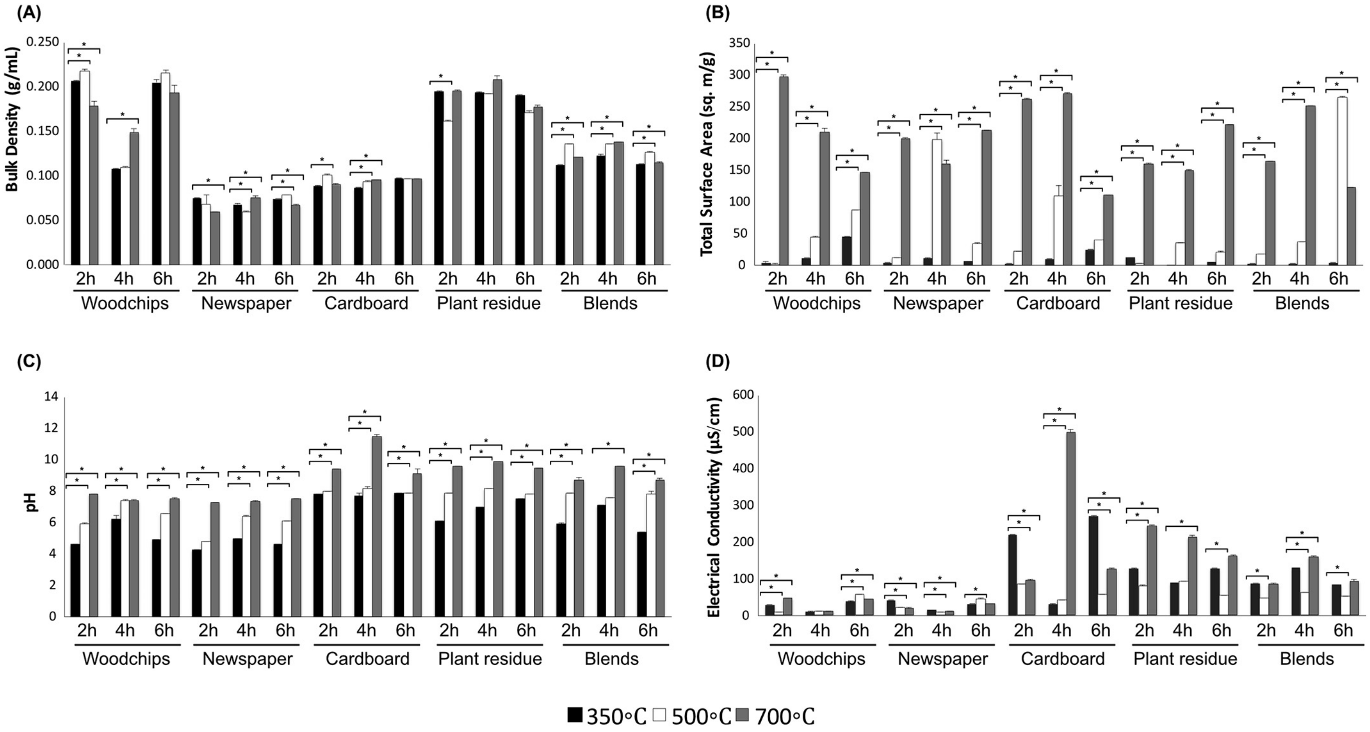

Fig. 2. Physicochemical properties of biochars from solid municipal waste: (A) Bulk density (g/mL); (B) Total surface area (sq. m/g); (C) pH; and (D) Electrical conductivity (µS/cm). * Student's *t*-test showing significant difference at $p < 0.05$.

with high TSA and high yield.

The pH values showed slight increases with increasing pyrolysis temperatures across all feed stocks, irrespective of retention time, reaching alkalinity (7.6–9.6) at the highest pyrolysis temperatures of 500–700 °C (Fig. 2C). Biochars from cardboard and plant residues that were pyrolyzed at 700 °C had alkaline pH (greater than 9) under all pyrolysis retention times. These biochars would be suitable for acidic soils, while biochars produced at 350 °C would be more suitable for alkaline soils. With respect to the electrical conductivity, no correlation was observed between pyrolysis temperatures or retention time. The highest electrical conductivity was observed in cardboard-based biochars that were pyrolyzed at 350 °C for 2 h (Fig. 2D).

3.2. *Effect of biochar amendment on soil properties*

The addition of biochars produced at a high temperature (700 °C) and applied at higher carbon-to-soil ratios (1–2%) resulted in alkaline soil. This change was particularly noticeable in soils amended with biochars prepared from woodchips, and cardboard (Fig. 3). The electrical conductivity and pH showed similar response in soils amended with newspaper and blends. Interestingly, soils amended with biochars produced at lower pyrolysis temperatures became slightly acidic (300–500 °C). Both the bulk density and soil aggregate stability were improved by the addition of biochar at the lower concentrations, especially by biochars from woodchip, plant residues, and cardboard (Fig. 3).

Overall, the addition of biochars to the soil increased the concentration of micronutrients compared to the soil control. The most noticeable increase in the soil Ca, K, Mg, P was observed in soils amended with biochars from woodchips, newspaper, and cardboard (Fig. 4). Contrastingly, this effect of nutrient release was not proportional to that contributing from biochars (Supplemental Tables 1–3). Among these biochars, newspaper biochar produced the highest increase in Ca, K, Mg, and P, especially at higher pyrolysis temperatures and lower biochar concentrations. This data suggests a link between pH and total surface area of biochar which appear to be determinant factor for retention of nutrients in soil. NO_3-N in soil increased upon the addition of biochars produced at higher pyrolysis temperature (700 °C) and amended at higher application rates. Higher K and NO_3-N were observed in soils amended with biochars produced from 25% blends of all feedstocks, pyrolyzed at 700 °C, and added at concentrations ranging from 0.5 to 2% and 1.0–2.0%, respectively.

3.3. *Effect of biochar amendment on soil leachate characteristics*

3.3.1. *Effect of biochar-amendment on pH of leachates*

Soils amended with biochars at different application rates demonstrated a significant increase in pH of leachates at day 120 of incubation compared to the control. Data in Fig. 5 suggest that, at higher pyrolysis temperatures and carbon application rates, the leachate pH increased significantly, particularly at 1 and 2% application rates ($p < 0.05$). The increased pH is attributable to the buffering effect of biochar pH. The latter also increased as the pyrolysis temperature increased. Leachate properties of cardboard-based biochar were found to have high pH and electrical conductivity when prepared at 350 °C temperature for 6 h and used at a biochar-to-soil incubation ratio of 1%. Biochar prepared from a 25% blend of each of the four feedstocks, prepared at 700 °C for 4 h, and applied at a 2% biochar to soil ratio produced leachate with the highest pH (6.8).

3.3.2. *Electrical conductivity of leachates*

The addition of biochars prepared from cardboard, plant residues and blends to the soil at different application rates produced a significant increase ($p < 0.05$) in EC compared to control at the beginning of incubation. Whereas, biochars from woodchips and

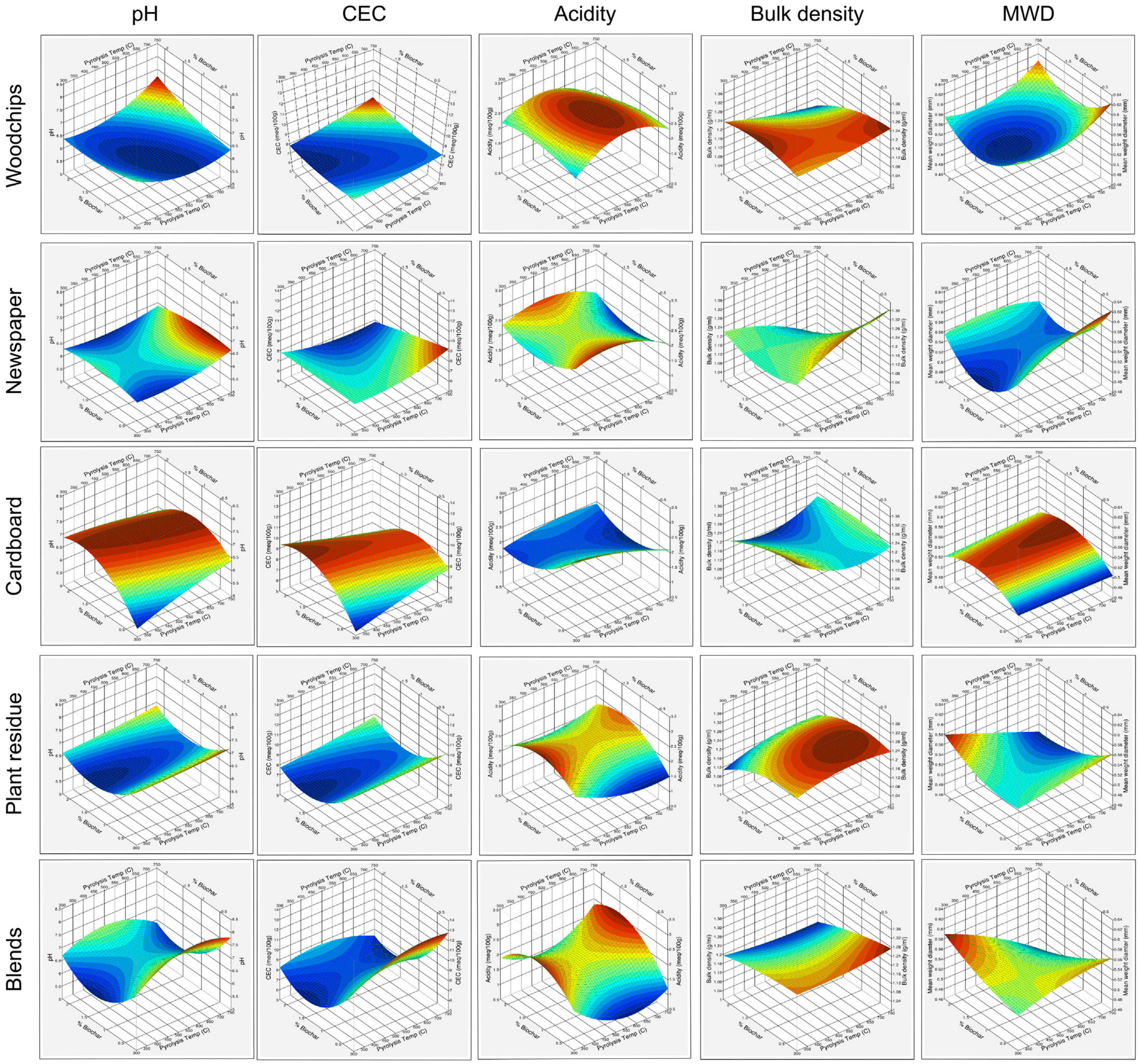

Fig. 3. Effect of production conditions and biochar application rate on select soil fertility parameters following 120 days of incubation. Note: Aggregate stability is measured as Mean Weight Diameter-MWD (mm).

newspaper did not produce any significant increases in EC on amended soil at the same time-point. Biochars form pyrolysis at 700 °C for 4 h and applied at 2% wt/wt biochar to soil yielded the highest electrical conductivity (Fig. 5).

3.3.3. *Water retention property of amended soil*

The addition of biochars significantly increased water retention in soil. Overall, biochars produced from woodchips, newspaper and plant residues increased soil water retention property (Fig. 5) while cardboard and feedstock blends required high pyrolysis temperatures and application rate to soil (2%) to contribute to high water retention.

3.3.4. *Nutrients analysis of leachates*

Apart from soil-amended with newspaper-based biochars, all other samples exhibited reduced Ca, Mg and K leaching irrespective of biochar pyrolysis conditions and biochar concentration in soil (Fig. 6), implying better retention of this element in the biochar-soil matrix (Fig. 6). As the Ca content in the initial soil was high (Supplemental Table 4), our results signify that newspaper based biochar may possess low sorption preference towards Ca. Contrastingly, sulfur leachate concentration from biochar-amended soils were significantly higher than in control. This could be attributed to a low affinity of these biochars to bind to sulfur ions.

4. Discussion

4.1. *Effect of pyrolytic conditions on biochar properties*

This study showed that pyrolysis temperatures and residence

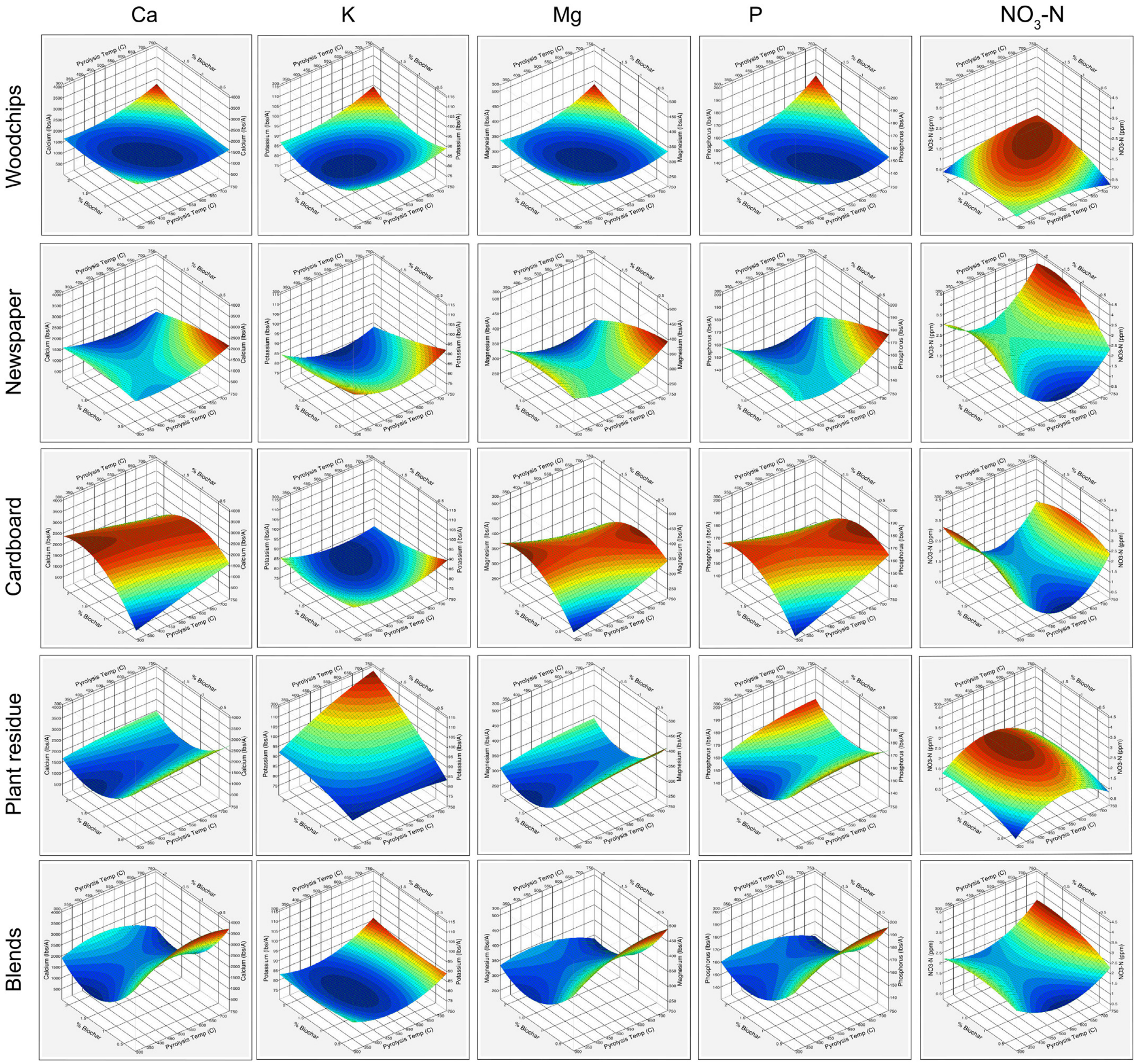

Fig. 4. Effect of production conditions and biochar application rate on nutrient content of amended soils after 120 days of incubation.

times significantly affect the physicochemical characteristics of biochar. High pyrolysis temperatures resulted in biochars with high TSA, pH and electrical conductivity but low yield. These properties were also dependent on the type of feedstocks utilized for biochar. Overall, high lignin source materials such as wood chips and plant residues exhibited greater yield and high bulk density.

The observed increases in biochar pH were consistent with prior studies (Bruun et al., 2011a; Brewer et al., 2009, 2011) and likely due to the extent of carbonization (Cantrell et al., 2012), which creates surface oxides and increases the proportion of ash in the biochar matrix. Cardboard and high-lignin feedstocks such as woody biomass resulted in higher porosity and electrical conductivity, as reported by Qian et al., 2015. High pyrolysis temperature, longer residence time and high lignin content in feedstocks resulted in biochars with a high total surface area. Similar data was reported by Ahmad et al. (2013), who attributed the increased surface area to compositional compounds (lignin, cellulose and hemicellulose) in feedstocks.

4.2. Effect of biochar on soil properties

Soil pH increased in amended soil containing biochars prepared from woodchips, and cardboards. This increase in pH of soil was a function of pyrolysis temperature and application rate. This observation is in agreement with the reported hypothesis of H^+ release from soil sorption sites attributed to single- and multi-element sorption by the amended soil (Ponizovsky et al., 2007; Mouta et al., 2008).

Several interacting factors such as type of feedstock, pyrolysis condition, application rate and characteristics of soil dictated the properties of amended soils. The surface chemistry and charge characteristics of biochar are predominantly controlled by

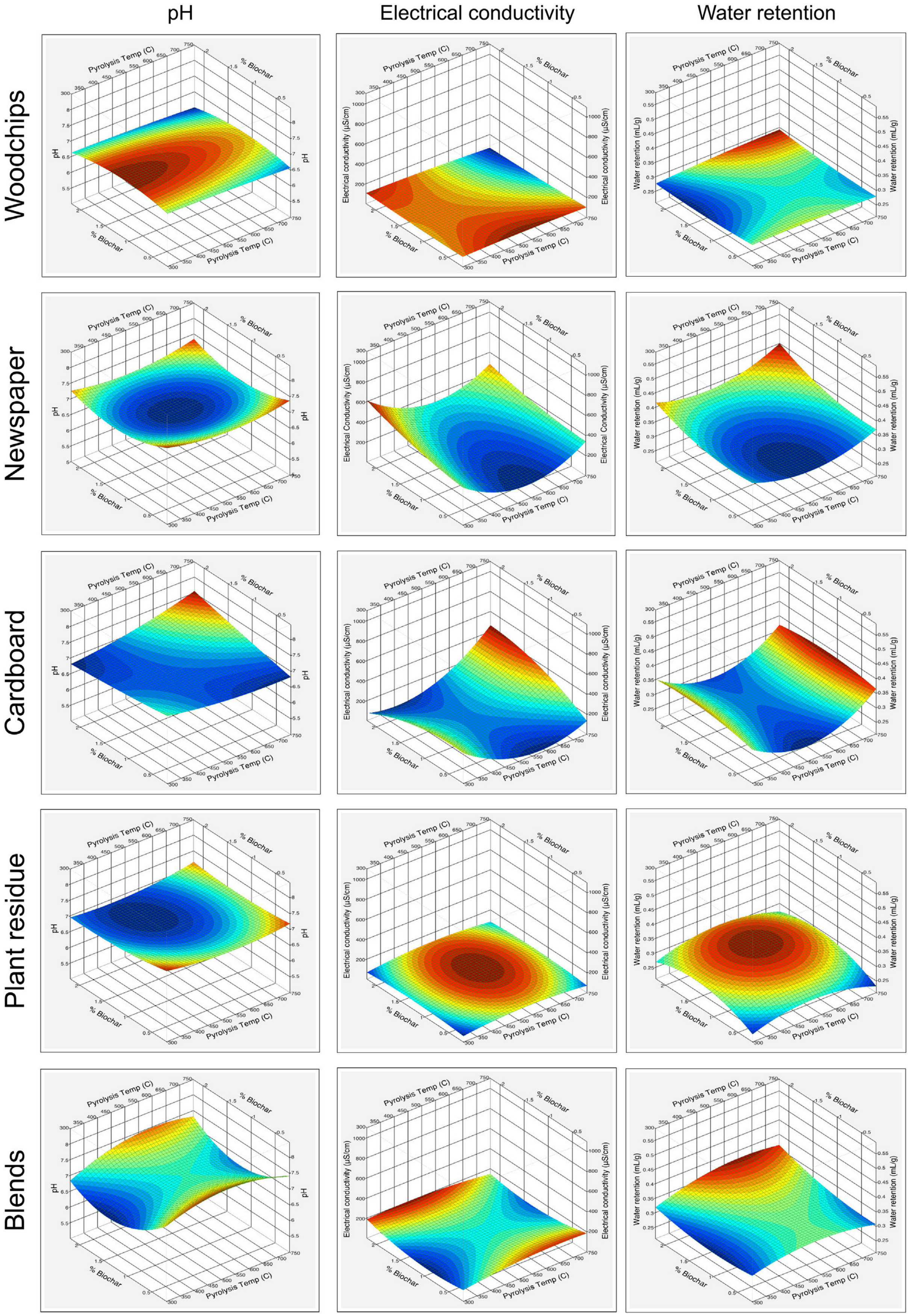

Fig. 5. Effect of production conditions and biochar application rate on soil leachate properties at the end of incubation period (day 120).

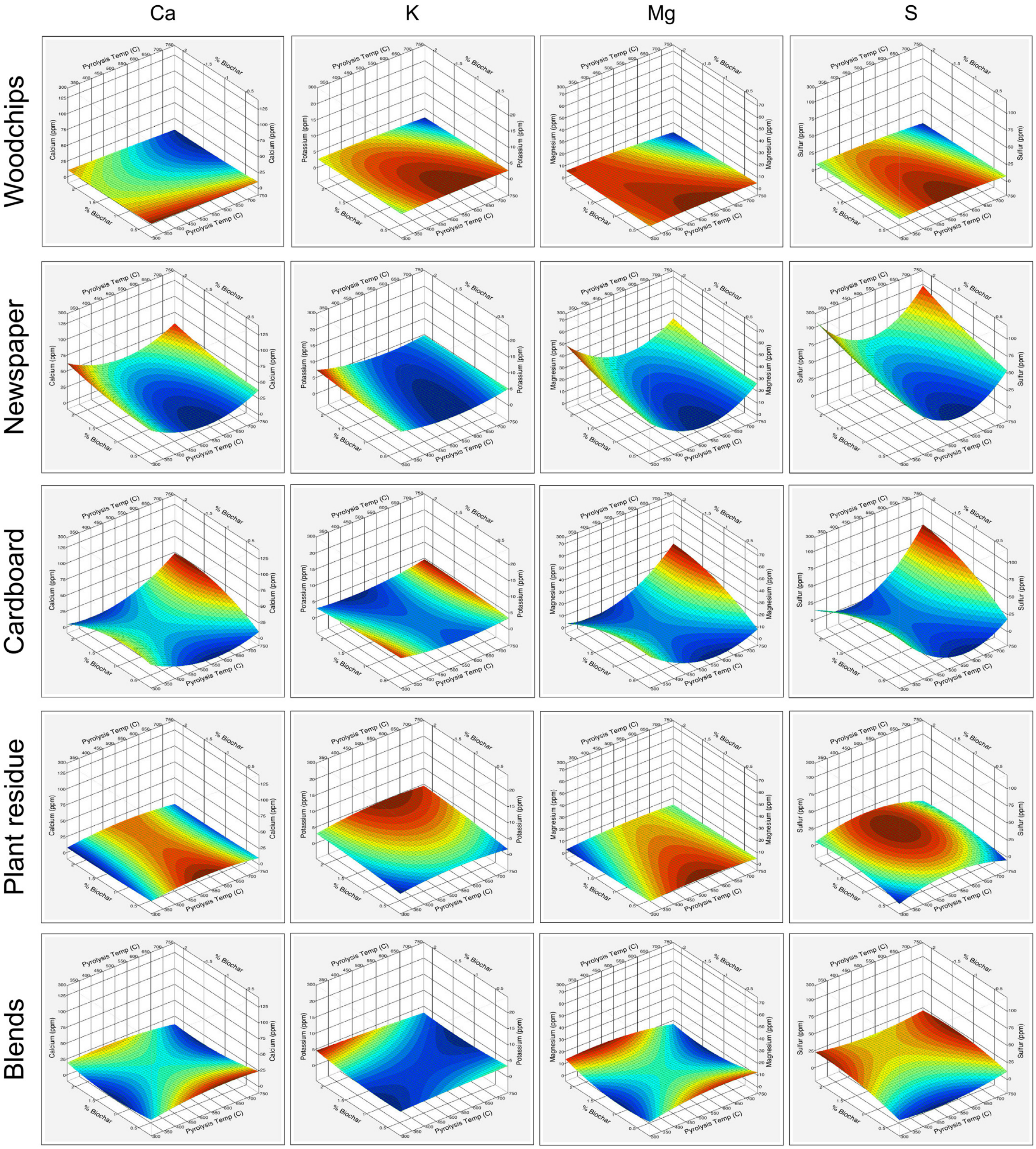

Fig. 6. Effect of production conditions and biochar application rate on micronutrients in soil leachate at the end of incubation period (day 120).

feedstock and pyrolysis conditions (Singh et al., 2010; Soucémarianadin et al., 2013). Also, ageing of biochar during soil incubation can also change surface chemistry due to sorption of microbial- and soil-derived organic matter (OM), resulting in an abundance of functional groups, which contribute to the modification of soil properties (Mukherjee et al., 2014; Qiu et al., 2009). The observed enhancement in soil aggregation is consistent with previous studies in which biochar was reported to increase soil aggregation by improving soil structure and infiltration (Amézketa, E., 1999; Liu et al., 2014). Water-stable aggregates, measured as mean weight diameter (MWD), are an important indicator of aggregate stability. Consistent with previous studies, results from this study showed that MWD increased with the application rate, particularly for biochars produced from cardboard feedstock

(Kemper and Chepil, 1965; Liu et al., 2014). Borchard et al. (2014), also observed that MWD of soil aggregates increased during a long-term biochar-soil incubation period. The significant positive effect of biochars on water retention was likely due to the surface area and porosity of these biochars. This significant enhancement in water retention can also be explained either by the polarity of these biochars, or their micropores' network, which physically retain water, or by improved aggregation (Busscher et al., 2010).

The application of biochars improved sorption of Ca, K, Mg, and P likely due to the alkalinity of amended soil, which helps in precipitation of elements due to the liming effect (Singh et al., 2010; Kookana et al., 2011). Also, the increased retention of nutrients biochar amended soil could be attributed to the surface area of biochar, facilitating greater interaction of nutrients with surface function groups on the biochar.

4.3. Effects of biochar on leachate properties

The pH of leachates collected from the soils changed from acidic to alkaline upon addition on biochars over 120 days of incubation, which is consistent with earlier studies showing the ability of biochars to influence pH and availability of soil nutrients (Rondon et al., 2007; Atkinson et al., 2010; Demeyer et al., 2001). The changes in leachate and soil properties were greatest in soils amended with woody biochars (woodchips, plant residues and blends) following 120 days of incubation. This could be due to the high lignin content and porosity leading to enhanced sorption capacity for selective nutrients (Novak et al., 2009).

Water retention was improved by the addition of biochar, most likely due to the intrinsic surface area (TSA) of biochars and the induced changes in pH, especially when feedstocks were pyrolyzed at 700 °C. Yaricoglu et al. (2015), also showed that pinewood biochars containing ash increased water holding capacity. Biochar has also been linked to increases in total porosity, leading to water retention in small pores and thus increasing water-holding capacity (Karhu et al., 2011).

A decrease in leachate Ca, K, and Mg content was found to be inversely dependent on pyrolysis temperature and total negative surface charge. The latter was greatly affected by the type of feedstock. The decrease in Ca and Mg content of leachates could be explained by surface functional groups and porosity, which can act as nutrient retention sites (Glaser et al., 2002; Singh et al., 2010).

According to the lyotropic series, Ca^{2+} and Mg^{2+} have a stronger affinity for surface exchange sites compared with K^+ (Bohn et al., 1985). Novak et al. (2009) observed that pecan shell biochars in Norfolk loamy sand produced leachates with lower Ca and Mg concentrations, higher K with greater biochar amendment rates within 25-days incubation.

The observed increase in NO_3-N within soils following incubation with biochars produced at higher temperature is consistent with the findings of Yao et al. (2012) and Dempster et al. (2012), who showed that NO_3^- leaching was reduced due to the addition of biochar to soil. NO_3^- residence time is greatly increased upon soil amendment with biochar because NO_3^- is weakly adsorbed by the biochar and is readily desorbed by water infiltration (Clough et al., 2013). However, by adding a C source, biochar may likely stimulate microbial growth and expansion, and immobilization of nitrogen leading to better retention (Bruun et al., 2011b).

5. Conclusions

In summary, pyrolysis conditions and feedstock greatly affected the physico-chemical properties of the biochars. For instance, pyrolysis of feedstock at lower temperatures for shorter duration increased biochar yield. Biochar prepared from woody feedstocks also exhibited higher bulk density when compared to newspaper or cardboard based biochars. Regardless of precursors, high pyrolysis temperatures significantly increased surface area, pH, and electrical conductivity of biochars. Mixed feedstock-based biochar exerted beneficial effect on soil including buffering capacity, water-holding capacity, and overall moisture levels in pots. Biochars produced at lower temperature (350–500 °C) and short retention time (1–2 h) seem to perform better in terms of soil water holding capacity, while those produced at a high temperature (700 °C) and longer retention time (4–6 h) were better at soil pH buffering. Hence, mixtures of these biochars may be required to achieve optimal performance in soils for which multiple deficiencies need to be addressed simultaneously.

This study demonstrated that biochar can be produced from organic solids typically found in municipal wastes and successfully used to enhance soil functions such as nutrient flux, soil pH, water and carbon storage. While further optimization is needed, it is clear that constituents of municipal solid municipal wastes hold promising potential as inexpensive feedstocks for manufacturing value-added biochar with varied and customizable physicochemical characteristics for soil amendments.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.01.061.

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