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RESEARCH ARTICLE

Comparative analysis of nutrients composition in biochar produced from different feedstocks at varying pyrolysis temperature

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ABSTRACT

Biochar has proved to be effective in improving soil fertility and it is important to know its nutrients variability as influenced by pyrolysis temperature and feedstock type for optimum agricultural productivity. In this experiment four different feedstocks from animal and plant sources were selected and pyrolysed at four different temperatures of 300, 400, 500 and 600 °C for 3 hours at a heating rate of 10 °C min^{-1}. The feedstocks were Corn cob (CC), Poultry litter (PL), Cow dung (CD) and Peanut shell (PS). The results showed that increase in pyrolysis temperature led to decrease in the concentration of many of the parameters analysed in the biochar. At the lowest temperature of 300 °C the highest contents of (0.62 %) N in CD, (66.4 mg g^{-1}) P in CC, (8.38 mg g^{-1}) K in CD, (16.2 mg g^{-1}) Ca in CC, (4 21 mg g^{-1}) Mg in CC, (0.28 %) S in CC, were observed. On the other hand, increase in temperature resulted to increase in C, pH, Ash content and the highest pH value of 10.17 was found in CD. From this study, it can be deduced that feedstocks from animal source shows a high range of nutrient when compared to feedstocks from plant source and likewise increase in temperatures led to decrease in some essential nutrient needed by plant for growth and stability in the soil.

Keywords: Biochar, pyrolysis, temperature, feedstock, nutrients

1. INTRODUCTION

It is no longer news that our dear world is being faced with so many factors which could either be man-made or naturally occurring, whose detrimental effects on the environment has led to great climate change globally. According to IPCC [1], it is proposed that if bold steps are not taken to combat these depleting factors then we might be greatly endangered in our environment, society and the world at large. According to Lal [2], the world population which is currently 6.7 billion, may increase to 9.2 billion by year 2050, thereby increasing these factors which pose harm to the world. Generally, daily human activities give birth to harmful substances which in turn depletes our earthly composition. Some of these harmful substances include excessive carbon dioxide (CO_2) produced from burning of fossil fuels, methane gas released from landfills and from the digestive tract of grazing animals, nitrous oxide from fertilizers, gases from industries, deforestation and lots more. Although, many global warming gases are more harmful than CO_2, but they are not as abundant as CO_2 in the atmosphere [1], this is why CO_2 is regarded as the major greenhouse gas known to man. Concentration of CO_2 in the atmosphere has increased from 280 ppm as at year 2009 [3] and is presently increasing at a rate of 2 ppm year^{-1} (0.5% per year) [4]. According to Lal [3], the concentration of CO_2 amongst other greenhouse gases (GHGs), has led to increase in frequency and intensity of extreme events such as drought, decrease in rainfall effectiveness, decrease in crop yield etc. In other to reduce the GHGs in the atmosphere, two key activities are relevant, which are reduce the emission of CO_2 into the atmosphere and the second option proposes increase the storage of atmosphere carbon in the soil and its added advantage it provides is the potential for enhancement in agricultural production. The primary way in which carbon can be stored into the soil is as soil organic matter, a complex mixture of carbon compounds consisting of decomposing plant and animal tissue, microbes and carbon associated with soil minerals. Soil amendments such as compost, animal and poultry manures have played a huge

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contributing factor to increasing soil organic matter to enhance soil fertility in the past. Although, various limitation have been attributed to the use of animal manure and compost [5]. Therefore, there is need to consider the use of alternative such as biochar, a potential for enhancement of agricultural productivity through soil improvement, environmental sustainability through waste reduction, water resource protection and carbon sequestration [6]. Biochar is a carbon rich product obtained by thermal decomposition of biomass with little or no oxygen at low temperatures [7]. According to research, biochar amendment has been reported to enhance soil physical, chemical, hydrological and biological properties [8-12]. From research, application of biochar to soil increases plant growth since biomass itself is a load of nutrients, Lehman and Rondon [13] reported significant high plant productivity from increase in soil nutrient as a result of the biochar applied. The effectiveness of biochar on crop growth depends on the biochar quality, application rate, soil type and crop species [5]. However, the feedstock and temperature of which a biochar is produced determine the chemical composition and nutrient present in a biochar [14-17]. In addition, Atkinson et al. [18] and Igalavithana et al. [5] reported that biochar produced at low temperature ≤ 300 °C are richer in nutrients and suitable for agricultural soil compared to those produced at higher temperature ≥ 600 °C. Kolton et al. [19] reported that efficiency of biochar can be attributed to its large surface area and pore space which makes it favourable for soil organisms that aid nutrient uptake by the plants. However, study and investigation on different pyrolysis temperature influencing the nutrient composition of biochar produced from different agricultural feedstocks including plants and animal sources have not fully gained much recognition. Therefore, this study investigates the effects of different pyrolysis temperature of 300, 400, 500 and 600 °C on nutrient composition of biochar produced from cow dung, poultry litter, peanut shell and corn cob feedstocks.

2. MATERIALS AND METHODS

2.1. Feedstock collection and biochar production

Feedstock materials from two plant and two animal sources were used for the purpose of this experiment. These feedstocks were Peanut shell (PS), Cow dung (CD), Poultry litter (PL) and Corn cob (CC). All the feedstock were sourced from different local farms in Akure, Southwestern, Nigeria. 10 kg each of CC, PL, PS and CD were cleansed, sundried, and the corn cob reduced into sizes ≤ 5 cm. Thereafter, the feedstock were pyrolysed in a muffle furnace at four different temperatures of 300 °C, 400 °C, 500 °C and 600 °C respectively for 3 hours at a heating rate of 10 °C min^{-1}. After pyrolysis, the biochar yield was determined mathematically by dividing the mass of the biochar produced by the mass of feedstock pyrolysed. In addition, the biochar produced were weighed using a weighing balance and finally sieved with a 2mm sieve in other to obtain uniformity. The sieved biochar samples were packaged in a plastic container and labelled for further analysis.

2.2. Determination of biochar nutrient composition

The chemical and nutrient analysis of the biochar were determined using standard methods and procedures described by International Biochar Initiative [20]. The parameters determined in the samples were: pH, Nitrogen (N), Potassium (K), Phosphorus (P), Calcium (Ca), Sulphur (S), Magnesium (Mg), Carbon (C), Hydrogen (H), Iron (Fe), Aluminum (Al), Zinc (Zn), Copper (Cu), Sodium (Na), Ash content, Cation Exchange Capacity (CEC) and Volatile Matters (VM). The pH was determined using 1:20 w/v biochar to water suspension ratio according to Rajkovich et al. [21] and measured using a portable pH meter (HANNA 016). Also, CEC was determined using ammonium acetate method as illustrated by Rajkovich et al. [21]. Cu, P, Mg, Ca, S, Na, K, Zn, Al and Fe were extracted from biochar samples by digestion in hydrogen peroxide (H_2O_2) and sulphuric acid (H_2SO_4) according to Wolf [39], thereafter, their concentrations in the biochar digest were determined on an atomic absorption spectrophotometer (AAnalyst 100, Perkin-Elmer, USA). C, H, N were determined through extraction using analytical techniques from the solution of biochar mixed into 1M HCl and allowed to stand overnight followed by mechanical shaking [22]. Volatile matter and ash content were determined using methods ASTM D1762-84 recommended by IBI [20].

3. RESULTS AND DISCUSSION

3.1. Effects of pyrolysis temperature on biochar yield

The biochar yield from all the pyrolysed feedstock ranged between 5.0 ± 0.02 – 58.0 ± 0.06 % and there was a decreasing trend in yield with increasing temperature as shown in Table 1. This is similar to the findings of many researchers as they also reported decrease in biochar yield with increasing temperature [23-26]. According to Sarfraz et al. [26] and Katyal et al. [27], high biochar yield at lower temperature could be attributed to partial combustion of biochar feedstock while a complete combustion at higher temperature, hence its lower yield. Also, lower yield at high temperature could be as a result of greater losses of volatile components at the higher pyrolysis temperatures [28] and the depolymerisation of compounds like cellulose and hemicellulose as well as combustion of organic materials [29, 17]. The highest biochar yield of 58.0, ± 0.06, 39.5 ± 0.6, 12.0 ± 0.04 and 7.5 ± 0.02 % were obtained at the lowest temperature of 300 °C from CD, PL, CC and PS feedstocks respectively while the lowest yield of 46.0, 36.5, 5.0 and 5.0 were obtained at the highest temperature of 600 °C from the respective feedstocks. The yield of biochar produced from each of the feedstock at the same temperature differ from one another because of the difference in the composition and properties of their feedstock.

Table 1. Biochar yield from different feedstocks pyrolysed under different temperatures

Biochar	Yield			
	Temperature (°C)			
	300	400	500	600
CD	58.0 ± 0.06	54.0 ± 0.2	50.0 ± 0.4	46.0 ± 0.46
PL	39.5 ± 0.6	38.5 ± 0.49	38.0 ± 0.05	36.5 ± 0.31
CC	12.0 ± 0.04	10.0 ± 0.02	6.0 ± 0.04	5.0 ± 0.05
PS	7.5 ± 0.02	6.0 ± 0.02	5.5 ± 0.05	5.0 ± 0.02

Values are mean ± Standard deviation
CD = Cow Dung, PL = Poultry Litter, CC = Corn Cob, PS = Peanut Shell

3.2. Effects of pyrolysis temperature on the physicochemical properties of biochar

From Table 2a, increase in temperature led to decrease in nitrogen concentration of biochar derived from all the feedstocks. This is also similar to Naeem et al. [23], Nwajiaku et al. [25], Sarfraz et al. [26], where the lowest temperature of resulted to higher N value. The highest average N content of 0.62 % was found in CD at the lowest temperature of 300 °C while the lowest average N content of 0.20 % was found in PS at the highest temperature of 600 °C. Decrease in N content could be attributed to its transformation and loss during pyrolysis process as temperature increases [25], this is as a result of volatilization of N during pyrolysis where N is removed through the loss of ammonium and nitrate [25]. Also, increase in pyrolytic temperature resulted to decrease in the phosphorus content present in all the biochars. The highest P content of 66.40 mg g^{-1} was found in CC at the lowest temperature of 300 °C while the lowest P content of 15.9 mg g^{-1} was found in PL at the highest temperature of 600 °C. However, this was different to the findings of Sarfraz et al. [26] and Naeem et al. [23] where the highest temperature recorded the highest P value. In the same manner, increase in pyrolytic temperature decreased the concentrations of K, Ca, Mg, H and S present in the biochars derived from all the feedstocks, this therefore showed that these elements were lost by volatilization. The highest values of 8.38 mg g^{-1} K content, 16.2 mg g^{-1} Ca content, 4.21 mg g^{-1} Mg content, 14.8 % H content and 0.28 % S content at the lowest temperature of 300 °C were found in CD, CC, CC, PL and CC, respectively, with their lowest values found in the highest temperature of 600 °C. The findings is similar to Nwajiaku et al. [25] where increase in pyrolysis temperature decreased K and Mg. However, Sarfraz et al. [26]; Naeem et al. [23] and Gaskin et al. [30] reported increase in temperature with increase in K, Ca and Mg contents. Nelissen et al. [31] and Al-Wabel et al. [32], differently reported decrease in H content and H and S contents respectively with increase in temperature. However, increase in pyrolytic temperature led to increase in the content of C, this is similar to the findings of Sarfraz et al. [26], Nwajiaku et al. [25] and Naeem et al. [23]. At a temperature of 600 °C, biochar derived from CC had the highest C and content of 31.4 % while the lowest temperature of 300 °C recorded the lowest values of C to be 3.8 % in PL. Moreover, this increase in carbon with increase in temperature shows that pyrolysis promotes carbonization [33] and this could be as a result of high degree of polymerization which makes carbon structure to be more condensed in the biochar [7].

From Table 2b, increase in pyrolytic temperature led to decrease in the contents of Fe, Al, Zn, Na, CEC and VM found in the biochar derived from some of the feedstocks. However, this was different to the findings of Sarfraz et al. [26], where increase in temperature resulted to increase in Fe and Zn. The highest Fe content of 18.40 ppm was found in CC at the lowest temperature of 300 °C while the lowest Fe content of 3.02 ppm was found in CD at the highest temperature of 600 °C. Al content decreased with increase in temperature in biochars derived from PS and PL but had fluctuations of values in CD and maintained equal but lowest content of 1.00 mol kg^{-1} at 500 °C and 600 °C while it exhibited the highest value of 2.32 mol kg^{-1} in CD at a temperature of 500 °C. Zn and Na and VM contents in biochar derived from all the feedstocks decreased with increase in temperature, with the highest values of 9.64 ppm of Zn, 2.91 mg g^{-1} of Na found in PL respectively and 96 % of VM in CD all at 300 °C. Similar to the findings of Sarfraz et al. [26], Naeem et al. [23], and Gaskin et al. [30], CEC decreased with increase in temperature with the highest value of 25.10 mol kg^{-1} at 300 °C in PS but only exhibited differently in PL with the temperature of 500 °C higher than 600 °C. However, the findings of Nelissen et al. [31] reported increase in CEC with increase in temperature. Decrease in CEC with increase in temperature could be attributed to degradation in volatile organic compounds and acid functional groups associated with negative surface charge of biochar [26]. Also, Jindo et al. [34] and Nelissen et al. [31] reported decrease in VM content with increase in temperature. Cu, pH and Ash contents increased with increase in temperature and these findings are similar to that of [23-26, 34]. The highest Cu content of 1.28 ppm was found in CD at 300 °C and lowest value of 0.04 ppm in PS at 600 °C. Increase in pyrolytic temperature led to increase in pH content as the level of acidity decrease and increase basicity of the biochar [35, 36], this could be attributed to the relative concentration of non-pyrolyzed inorganic elements, situated in the original feedstocks [28], and as a result of higher ash contents present at higher temperature [23] and hydrolysis of salts of Ca, K and Mg [30]. The highest pH value of 10.17 was found in CD at 600 °C while the lowest biochar pH was 7.11 at 300 °C in CC. Also, the ash content of 98 % at 600 °C was found in PS and the lowest was found at 300 °C in PL. Peng et al. [37] reported increase in ash content and decrease in volatile matter with increase in temperature. In this study, biochar produced at low temperature showed higher nutrients from all the elements analysed and they can be referred to as agricultural soil amendment [14, 18].

Table 2a. Elemental composition of biochar derived from different feedstocks at different pyrolysis temperatures

Biochar Feedstock	Temp °C	N (%)	P mg g^{-1}	K mg g^{-1}	Ca mg g-1	S %	Mg mg g^{-1}	C %	H %
PS	300	0.3 ± 0.02	23.4 ± 0.36	2.85 ± 0.02	13.11 ± 0.02	0.25 ± 0.02	2.14 ± 0.03	13.4 ± 0.1	6.7 ± 0.04
	400	0.24 ± 0.02	22.2 ± 0.25	2.75 ± 0.05	6.21 ± 0.03	0.20 ± 0.01	1.86 ± 0.06	16.10 ± 0.2	4.32 ± 0.04
	500	0.22 ± 0.03	20.3 ± 0.55	2.51 ± 0.03	3.11 ± 0.04	0.18 ± 0.02	1.76 ± 0.04	21.1 ± 0.9	3.84 ± 0.05
	600	0.20 ± 0.02	17.50 ± 0.05	2.44 ± 0.05	2.00 ± 0.03	0.10 ± 0.02	0.70 ± 0.02	23.4 ± 0.1	2.1 ± 0.03
CC	300	0.59 ± 0.07	66.40 ± 0.58	2.01 ± 0.06	16.2 ± 0.02	0.28 ± 0.04	4.21 ± 0.03	15.7 ± 0.04	14.18 ± 0.1
	400	0.50 ± 0.02	66.3 ± 0.23	1.84 ± 0.01	9.30 ± 0.03	0.22 ± 0.04	3.18 ± 0.03	25.30 ± 0.07	12.24 ± 0.05
	500	0.42 ± 0.04	66.2 ± 0.17	1.67 ± 0.03	8.10 ± 0.04	0.16 ± 0.04	3.14 ± 0.05	29.1 ± 0.13	8.60 ± 0.1
	600	0.38 ± 0.04	65.0 ± 0.02	1.52 ± 0.06	7.90 ± 0.1	0.08 ± 0.00	2.91 ± 2.03	31.4 ± 0.07	4.49 ± 0.05
CD	300	0.62 ± 0.02	24.1 ± 0.02	8.38 ± 0.07	4.28 ± 0.05	0.06 ± 0.01	2.36 ± 0.04	12.6 ± 0.56	7.8 ± 0.1
	400	0.50 ± 0.01	22.8 ± 0.03	6.0 ± 0.03	2.14 ± 0.03	0.03 ± 0.00	1.06 ± 0.09	21.1 ± 0.19	4.17 ± 0.28
	500	0.42 ± 0.01	21.0 ± 0.05	3.52 ± 0.03	1.96 ± 0.05	0.02 ± 0.00	0.62 ± 0.05	24.5 ± 0.06	3.12 ± 0.13
	600	0.38 ± 0.03	19.75 ± 0.05	2.68 ± 0.04	1.86 ± 0.03	0.02 ± 0.00	0.58 ± 0.04	27.2 ± 0.62	2.46 ± 0.07
PL	300	0.36 ± 0.06	19.1 ± 0.98	4.13 ± 0.09	2.56 ± 0.23	0.03 ± 0.00	1.21 ± 0.03	3.80 ± 0.02	3.4 ± 0.04
	400	0.34 ± 0.03	17.4 ± 0.09	4.02 ± 0.11	2.46 ± 0.41	0.03 ± 0.00	1.06 ± 0.07	9.8 ± 0.16	2.68 ± 0.06
	500	0.32 ± 0.03	17.2 ± 0.21	3.76 ± 0.05	1.78 ± 0.10	0.01 ± 0.00	0.62 ± 0.04	19.3 ± 0.17	1.15 ± 0.07
	600	0.30 ± 0.01	15.9 ± 0.18	3.45 ± 0.06	1.16 ± 0.05	0.01 ± 0.00	0.58 ± 0.04	27.2 ± 0.21	1.01 ± 0.06

PS = Peanut Shell CC = Corn Cob CD = Cow Dung PL = Poultry Litter
Mean Values ± Standard deviation

Table 2b. Elemental composition of biochar derived from different feedstocks at different pyrolysis temperatures

Biochar Feedstock	Temp °C	Fe ppm	Al mol kg^{-1}	Zn ppm	Cu ppm	Na mg g^{-1}	pH	Ash %	CEC mol kg^{-1}	VM %
PS	300	9.25 ± 0.02	1.50 ± 0.02	1.61 ± 0.03	0.04 ± 0.00	0.90 ± 0.02	8.41 ± 0.04	90.40 ± 0.41	25.10 ± 0.06	92.60 ± 0.51
	400	8.06 ± 0.07	1.46 ± 0.02	1.33 ± 0.1	0.09 ± 0.01	0.76 ± 0.04	8.46 ± 0.07	96.1 ± 0.25	24.26 ± 0.04	66.11 ± 0.04
	500	7.88 ± 0.1	1.36 ± 0.01	1.15 ± 0.05	0.10 ± 0.02	0.74 ± 0.03	8.75 ± 0.04	97.5 ± 0.5	23.34 ± 0.05	62.22 ± 0.1
	600	6.81 ± 0.09	1.24 ± 0.07	1.1 ± 0.07	0.15 ± 0.02	0.52 ± 0.05	8.79 ± 0.06	98.0 ± 0.02	22.06 ± 0.08	34.22 ± 0.02
CC	300	18.4 ± 0.03	1.24 ± 0.05	7.88 ± 0.05	0.56 ± 0.06	1.23 ± 0.04	7.11 ± 0.04	53.5 ± 0.05	22.14 ± 0.05	85.60 ± 0.06
	400	13.56 ± 0.03	1.02 ± 0.08	7.59 ± 0.03	0.45 ± 0.02	1.20 ± 0.02	7.13 ± 0.03	68.2 ± 0.04	21.20 ± 0.03	52.90 ± 0.02
	500	13.45 ± 0.05	1.00 ± 0.02	6.96 ± 0.06	0.40 ± 0.03	0.98 ± 0.02	7.54 ± 0.04	80.4 ± 0.02	20.16 ± 0.04	49.00 ± 0.76
	600	13.25 ± 0.02	1.00 ± 0.02	6.91 ± 0.1	0.37 ± 0.05	0.96 ± 0.02	7.86 ± 0.04	89.6 ± 0.07	20.00 ± 0.16	38.90 ± 0.08
CD	300	8.15 ± 0.07	2.30 ± 0.16	7.59 ± 0.05	1.28 ± 0.07	2.32 ± 0.1	9.90 ± 0.17	17.9 ± 0.18	22.14 ± 0.15	96.00 ± 0.06
	400	4.57 ± 0.34	2.14 ± 0.01	5.51 ± 0.47	0.21 ± 0.05	2.16 ± 0.18	10.02 ± 0.17	26.7 ± 0.96	21.20 ± 0.18	84.30 ± 0.53
	500	4.20 ± 0.12	2.32 ± 0.09	4.48 ± 0.09	0.19 ± 0.02	1.82 ± 0.07	10.05 ± 0.08	30.0 ± 0.55	20.16 ± 0.11	80.62 ± 0.34
	600	3.02 ± 0.06	2.14 ± 0.08	2.19 ± 0.08	0.14 ± 0.01	1.66 ± 0.12	10.17 ± 0.03	44.6 ± 0.55	20.06 ± 0.12	68.48 ± 0.12
PL	300	6.59 ± 0.07	1.86 ± 0.02	9.64 ± 0.07	0.27 ± 0.06	2.91 ± 0.04	9.39 ± 0.06	15.8 ± 0.22	22.14 ± 0.06	80.90 ± 0.18
	400	5.45 ± 0.1	1.65 ± 0.04	2.20 ± 0.03	0.17 ± 0.02	1.35 ± 0.04	9.57 ± 0.09	21.6 ± 0.34	20.33 ± 0.09	60.11 ± 0.3
	500	5.08 ± 0.11	1.56 ± 0.07	1.12 ± 0.06	0.12 ± 0.04	1.31 ± 0.08	9.77 ± 0.06	36.0 ± 0.05	17.26 ± 0.06	39.70 ± 0.27
	600	5.10 ± 0.15	1.46 ± 0.1	0.78 ± 0.04	0.04 ± 0.00	1.17 ± 0.04	9.96 ± 0.07	66.7 ± 0.3	18.33 ± 0.1	29.63 ± 0.08

PS = Peanut Shell CC = Corn Cob CD = Cow Dung PL = Poultry Litter
Mean Values ± Standard deviation

3.3. *Effect of feedstock on nutrients composition of biochar*

In addition to analyzing the effect of temperature, this study also analyzed the effect of feedstocks on nutrient composition of biochar. The N and Cu contents followed a descending order of CD>CC>PL>PS. Also, P and Mg contents followed the order of CC>CD>PS>PL. Concentrations of Ca, S, Fe and H followed the order of CC>PS>CD>PL with the two plant sources biochar having the highest concentrations of these nutrients. However, K, Al and pH exhibited the highest concentrations in the two biochars from animal sources in the order of CD>PL>PS>CC. The two animal sources CD and PL exhibited the highest pH compared to the other plant sources, this could be due to the higher amount of basic salts found in their feedstocks [9]. Biochars derived from plant sources exhibited higher concentrations of Ash, CEC and C while the animal sources exhibited higher concentrations of Na, Zn and VM. Comparing PL and PS both from two different sources, PL exhibited the highest concentration of N, K, Al, Zn, Na, Cu, pH and C than PS, while for P, Ca, Fe, S, Mg, Ash, CEC, VM and H the opposite was the case. Gaskin, et al. [30] reported higher concentrations of `N, P, K, Ca, Mg, Cu, Fe, Na, and Zn in Poultry Litter than in Peanut Hull (PN). PS and CC both from plant source exhibited the higher ash content than the other biochars from animal sources, this was different to findings of Koutcheiko et al. [38] who reported high ash content in biochar derived from manures.

Also, CC showed had higher nutrients (P, Ca, S, Mg, H, Fe, Zn, Cu and Ash) concentrations than CD, while the concentrations of K, C, Al, Na, pH, VM were higher in CD. However, there was no significant difference in the concentrations of N and CEC present in both biochars.

4. CONCLUSIONS

From this research it can be concluded that pyrolysis temperature and feedstock have significant effect on the nutrient composition of biochar which in turn affects their suitability as soil amendment. The yield of biochar decreased while ash content increased with increasing pyrolysis temperature. The pH of all biochar was found to increase with increasing temperature while CEC decreased. The concentration of N decreased with increasing temperature and a high proportion of N was conserved in the biochar at lowest temperature. However, other elements such as P, K, Mg and Ca decreased with increasing pyrolysis temperature and therefore this indicates a tendency of these elements to become less available to the soil. Therefore, the suitability of biochar for optimum soil fertility should be pyrolysed at lower temperature with feedstock properly considered.

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