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Nitrogen and phosphorus release from dehydration products of urine mixed with pine bark feedstock, biochar types and ash

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Human urine contains large quantities of nitrogen (N) and phosphorus (P), yet most of it is lost to the environment untreated, resulting into nutrient loss and environmental pollution. Although several studies have evaluated nutrient recovery from urine, little is known about how pine bark (PB) and its derivatives (biochar and ash) influence N and P release from dehydrated urine products in soil. This study evaluated effects of various products derived from dehydration of urine, mixed with solid materials from pine bark (PB) on mineral nitrogen (N) and phosphorus (P) availability in soil. The PB materials included feedstock, biochar (pyrolysed at 350 and 650 °C) and ash. The mixtures of urine and these materials were dehydrated at 45 and 60 °C in the oven. Others from PB were also dehydrated in a glasshouse (G). In the experiments, the dehydration products were applied at the recommended N (100 kg ha^{-1}) rate for spinach. The soils (100 g) were incubated at field capacity and 25 °C temperature. Destructive sampling was done at days 0, 7, 14, 21, 28, 42, and 56 for the first and second experiment, with analysis of pH, ammonium- and nitrate-N and extractable P per sampling day. Nitrate-N increased with a decrease in ammonium-N. In experiment 1 and 2, ash dehydrated at 45 °C (ash 45) and ash dehydrated at the glasshouse (ash G) maintained the highest nitrate-N (37.2 and 38.7 mg kg^{-1}, respectively), suggesting efficient N recovery and release. Overall, ash was the most effective in increasing N availability. The results shows that the composition of recovery media including its pH strongly influence nutrient recovery and release of nutrients from the urine-based products.

Keywords Dehydration, Mineral nitrogen, Phosphorous, Urine-based products

Globally, over 80% of wastewater, which includes human urine, is discharged to the environment with little or no treatment[1]. Large amount of nutrients such as nitrogen (N), phosphorous (P) and potassium (K) in the wastewater contribute negatively to the environment[2]. The high concentration of total N (0.74%), K (1.62%), and P (0.02%) in human urine suggest that, if it source-separated through ecological sanitation approaches[1,3], its application could have a significant contribution to soil fertility. However, the N in urine could be lost to the atmosphere through ammonia volatilisation, while practical challenges associated with transportation costs, due to a huge proportion of human urine being water, makes it complicated to benefit from fertilisation with urine. Recovery of N by using different substrates has, therefore, become an emerging research focus. Adding a substrate that will increase or lower pH, could inactivate the urease enzyme responsible for hydrolysis of urea to ammonia and result in absorption of the N, which allow for dehydration of the excess water, producing a potentially valuable product.

Different urine-based products have been produced by modifying urine pH followed by dehydration, resulting products with high nutrient concentrations and monetary value[4,5]. Modifying urine with calcium hydroxide ($Ca(OH)_2$) followed by drying resulted in a product with 9.3, 0.7 and 3.9% N, P and K, respectively[5]. Furthermore, a urine-based fertiliser produced with wood ash produced a nutrient-rich end product with concentration of nutrients (9.7, 1.5 and 8.4% N, P and K, respectively) than in the original fresh urine[5]. However, it is worth noting that the elemental composition of the substrate/medium could affect the nutrient composition of the final fertiliser material produced. The use of biochar may therefore produce a carbon-rich fertiliser material, which can both increase carbon sequestration and improve soil fertility[6]. Having different solid media for dehydration would produce a variety of urine-based fertiliser materials which differ in their contributions to

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nutrients availability in the soil. Understanding nutrient release patterns of the different urine-based products in the soil is paramount for evaluating their fertiliser value.

Pine bark (PB) was used in this study due to its abundance as organic waste in South Africa and also its acidic pH (3.02). This is of paramount importance as urease activity, which rapidly hydrolyses urea in urine, can be supressed at both low and high pH, reducing N losses. Furthermore, the carbon composition of this material could influence retention and release N and improve soil C storage when added to soils. Pine bark with a higher C: N contributes to slower degradation and potentially gradual nutrient release. Preliminary findings in our study showed that PB-based products retained more N from urine, with biochar at 650 °C showing the highest N recovery (> 100%). Additionally, literature shows a research gap in the use of locally available plant-based materials particularly PB for N recovery from urine.

Preliminary results have shown that application of acidic pine bark products and dehydrating at 45 and 60 °C recovers more N (2.23 and 2.96%, respectively). The contributions of the urine-pine bark waste products to nutrient release could be affected by the rate of degradation of the different substrates, which depends on the C/N ratio, and lignin content[7]. Furthermore, the solubility of potentially free (not adsorbed) urea could depend on the characteristics of the products together with those of the soil. However, no evidence could be accessed in the literature, on the effects of dehydrated urine-enriched pine bark waste products on nutrient release patterns in soil and there is limited literature on their effects on crop productivity. Panigrahi[8] reported that urine-enriched coconut shell biochar resulted in a better French bean growth and yield, reflecting and confirming the nutrient availability in soils. No previous research has investigated the nutrient release pattern of urine-enrichment products of raw pine bark (feedstock), biochar and ash from pine bark.

Some studies have evaluated nutrient recovery from urine using stabilisation and dehydration methods, but there is limited information on the use of organic waste materials such as pine bark (abundant in South Africa) and their biochar and ash, which vary in their carbon contents, aromaticity, pH and the CCE. Most previous work has focused on different media types, without considering how different material properties influence nutrient retention and release in soil. This study differs by using locally available plant-based wastes with distinct pH and chemical characteristics, applying a combination of dehydration temperatures. Including a glasshouse dehydration would assist to produce larger volumes of materials with low energy costs for drying. Additionally, while nitrogen from urine has been studied with ash, biochar from other organic materials, no literature could be found where the feedstock was used. Furthermore, most studies do not consider the release patterns of the stored or recovered N. The work provides new insight into how these factors affect nitrogen and phosphorus availability in soil, which has not been extensively studied. This evident the need to understand the contribution of urine-enriched products from pine bark on availability of N and P, in order to understand their contribution to soil fertility. The objective of this study was to determine the effect urine-based products derived from pine bark and its biochar and ash, dehydrated at 45 and 60 °C and under glasshouse (G) conditions, on the release of ammonium- and nitrate-N, and available P in amended soil.

Methods and materials

Experimental sites and soil

The incubation study was conducted at the University of KwaZulu Natal, Pietermaritzburg campus (29° 37' 33.9" S; 30° 24' 14'E), South Africa. The soil used in this study was collected under natural vegetation at the Ukulinga research farm of the University of KwaZulu-Natal, South Africa. The soil was loam in texture and classified as Westleigh[9], which was translated to Plinthic Acrisols[10]. Bulk soil samples were collected from the 0–20 cm depth, mixed, homogenised, air-dried, and sieved (< 2 mm), before analysis. The clay content of the samples was estimated using the near infrared reflectance (HTS-XT, Bruker, Germany), while total carbon (C) and nitrogen (N) were measured using the LECO Trumac CNS Autoanalyser (Leco corporation, 3000, Lakeview, Ave, ST, Joseph, MI, USA)). Phosphorus was extracted with the AMBIC-2 method[11] and analysed with a UV/VIS spectrophotometer following the molybdenum blue method[12]. Soil pH, exchangeable bases and acidity were analysed using standard methods[13]. The characteristics of the soils are shown in Table 1.

Property	Acrisols
Clay (%)	29
Bulk density (g cm^{-3})	1.24
pH $_{(KCl)}$	5.08
Total carbon (%)	1.95
Total nitrogen (%)	0.165
C/N	11.8
Extractable phosphorus (mg/kg)	3.86
Exchangeable potassium (cmolc/kg)	0.397
Exchangeable calcium (cmolc/kg)	8.79
Exchangeable magnesium (cmolc/kg)	7.48
Exchangeable acidity (cmolc/kg)	0.05
Acid saturation (%)	0

Table 1. Characteristics of the soil used in the study.

Urine-based product production and characterisation

Pine bark waste (feedstock), and biochars and ashes from this waste, was used in this study. The feedstock were ground to < 2 mm particle size using a Retsch KG 5657 HAAN (West Germany) machine and stored in plastic bags. Portions of feedstock samples were heated at 750 °C for 6 h in a muffle furnace to produce ash. Additionally, other portions of the feedstock samples were pyrolyzed at 350 and 650 °C in a muffle furnace, with limited oxygen for 2 h. The characteristics of the media are similar to those by Vilakazi et al.[14]. Another biochar was produced using a kiln (Figure S1) at Ukulinga Research Farm, which was fabricated by the School of Engineering, at the University of KwaZulu-Natal. Proximate analysis results for this kiln biochar showed 58.3% volatile matter, 40.8% fixed carbon and 0.82% ash and the total C, N, P and K were 65, 0.32, 0.005 and 0.355%, respectively. The pH was determined in KCl at a ratio of 1:10[15] and calcium carbonate equivalent was evaluated following the method by[16]. The pH and calcium carbonate equivalent (CCE) of the biochar produced in the kiln were 4.32 and 8.92%, respectively.

Artificial human urine (AHU) used this study had 12.2 g L^{-1} urea, 0.17 g L^{-1} uric acid, 0.45 g L^{-1} creatinine, 1.49 g L^{-1} tri-sodium citrate, 3.17 g L^{-1} sodium chloride, 2.25 g L^{-1} potassium chloride, 0.805 g L^{-1} ammonium chloride, 0.17 g L^{-1} sodium bicarbonate, 0.445 g L^{-1} calcium chloride, 0.5 g L^{-1} magnesium sulphate, 1.29 g L^{-1} disodium sulphate, 0.5 g L^{-1} monosodium phosphate and 0.55 g L^{-1} disodium phosphate[17]. The artificial human urine (AHU) contained multiple components, with their concentrations falling within the physiological ranges observed in normal human urine.

For the urine-based products, 50 g of feedstock, biochar or ash were added initially to each storage glass containers and urine was added and the mixtures were stirred for 5 s[18] followed by drying in ovens at 45–60 °C to allow rapid dehydration. Fresh urine was added weekly at a rate of 4.5 (45 °C) and 5.1 L m^{-2} (60 °C), with drying after each addition. The experiment ran for 28 days (Six urine additions), with 29 mL (45 °C) and 33 mL (60 °C) per addition. To produces materials on a large-scale the urine- feedstock, kiln biochar and ash were dehydrated under glasshouse conditions (G), with the cooling system switched off and no temperature control, resulting in temperatures ranging from a minimum of 9 °C to a maximum of 57 °C. A sample of 7 kg of each medium was added initially to plastic basins, followed by AHU application at a rate of 5.1 L m^{-2}, and after each application the mixtures were stirred and allowed to dehydrate. Recovered N as % of N in the urine added, pH, Total carbon (C) and nitrogen (N) were measured.

Experimental design

The incubation experiments were conducted simultaneously. In experiment 1 (Sect. 2.3.1), eight urine-based products derived pine bark feedstocks, biochar (pyrolysed at 350 and 650 °C), and ash, each dehydrated at 45 and 60 °C. These products were applied to 100 g of soil at the recommended N rate (100 Kg N ha^{-1}). In experiment 2 (Sect. 2.3.2), PB derived materials (feedstock, kiln biochar and ash, dehydrated at the glasshouse) were applied at the same rate as in experiment 1. Experimental measurements and management were consistent across all two experiments.

Incubation experiment 1

The first incubation experiment was set up in a completely randomised design with 8 urine-based products, with three replicates. The treatments of the urine-based products were from feedstock, biochars (350 and 650 °C), ash, all dehydrated at 45 and 60 °C, were used. The treatments consisted of feedstock products dehydrated at 45 °C and 60 °C (feedstock 45 and feedstock 60, respectively); ash products dehydrated at 45 °C and 60 °C (ash 45 and ash 60, respectively); biochar produced at 350 °C, then dehydrated at 45 °C and 60 °C (biochar 350 45 and biochar 350 60, respectively); and biochar produced at 650 °C, then dehydrated at 45 °C and 60 °C (biochar 650 45 and biochar 650 60, respectively). The products were applied to 100 g of soil at the recommended N rate for spinach (equivalent to 100 kg ha^{-1}). Unamended soil (no urine-based product) was also included as a control. The soil + urine-based product mixtures were placed in 500 ml plastic containers, which were tightly closed with lids and had four holes drilled below the rim to allow gas exchange. The soils were maintained at 100% water holding capacity, and the moisture was corrected weekly throughout the incubation based on weight loss. The soils were incubated in a constant temperature room at 25˚C with destructive sampling at 0, 7, 14, 21, 28, 42, and 56 days. The samples were analysed for ammonium- and nitrate-N, extractable P and soil pH.

Incubation experiment 2

The second incubation experiment was set-up the same way as the first one (Sect. 2.3.1) in terms of management. Urine-based products from the feedstock, biochar and ash dehydrated in the glasshouse (feedstock G, kiln biochar G and ash G), with all other materials, management and measurements being the same.

Analysis

Ammonium- and nitrate-N were determined using the Gallery Discrete Analyzer[19] after extraction with 2 M KCl solution. For this, soil (2 g), suspended in 20 mL of 2 M KCl solution, was shaken on a reciprocal shaker (Model E5850 Thomas Scientific, Swedesboro, NJ, USA) at 180 cycles per minute for 30 min, followed by filtration using Whatman No. 1 filter paper into storage bottles. Extractable P was determined calorimetrically by the molybdenum blue method[12].

Statistical analysis

The results of soil pH, mineral-N (ammonium- and nitrate-N) and extractable P were analysed using GenStat 18th edition (VSN International 2015) by subjecting them to the two-way analysis of variance (ANOVA). The results were analysed separately for different sampling days. The least significant difference (LSD) was used to compare the treatment means at 5% level, while Tukey test was applied to separate treatment means at $p < 0.05$

to get mean difference. Mean separations in the tables were determined using the Tukey test (denoted by letters), whereas error bars in the figures were derived from the LSD test.

Results

Characteristics of the urine-based products

The recovery of N from added urine was significantly higher in biochar 650, exceeding 100% at both dehydration temperatures (45 and 60 °C), compared to ash G. The pH was also significantly higher for ash dehydrated at 45 and 60 °C than for feedstock dehydrated at the glasshouse and 60 °C. Ash treatments had significantly lower carbon (C) content compared to biochar 650 60, which had 80% C. The highest N content was recorded for biochar 650 60 (2.97%), while ash G had the lowest N (1.38%). The C: N ranged from 1.26 to 27.9, with biochar 650 dehydrated at 45 °C and 60 °C having significantly higher C: N than ash at all dehydration temperatures.

Changes in ammonium-N

There was a sharp increase in ammonium-N concentration within the first 7 days of the incubation for all the treatments (Fig. 1a, and b). Ammonium-N concentration decreased throughout the incubation period from day 7 up to 42 (Fig. 1a and b) and stabilised between days 42–56.

Changes in nitrate-N

Application of urine-based products significantly increased nitrate-N concentration (Fig. 2a, and b). The maximum nitrate-N was 37.159 mg kg^{-1} (ash 45) at day 28 (Fig. 2a). All treatments showed an increase from day 0, stabilizing between day 28 and day 56, following a similar trend. The order of effectiveness was as follows: ash 45 > feedstock 45 = feedstock 60 > ash 60 > biochar 650 60 < biochar 350 45 > biochar 650 45 > biochar 350 60 > control. Of the products dehydrated in the glasshouse, the one from ash showed the higher increase in nitrate-N than those from feedstock and kiln biochar (not significantly different), especially from day 14, reaching a maximum of 38.7 mg kg^{-1} and stabilizing between day 28 and day 56 (Fig. 2b). The control had lower nitrate N that all other treatments throughout the incubation period (Fig. 2b).

Changes in extractable P

Extractable-P decreased in all treatments until day 28, except for ash 60, which increased and peaked at day 21, reaching 29.8 mg kg^{-1} (Fig. 3a), followed by decrease until day 28. Following the decrease, all the treatments increased between days 28–42, then stabilised until day 56 (Fig. 3a and b). Extractable-P increased for both kiln biochar and ash, reaching a maximum of 44.2 mg kg^{-1} on day 21, followed by a decrease until day 28 (Fig. 3b). In contrast, feedstock showed a decrease in extractable P from day 0 until day 28.

Changes in soil pH

There were significant differences in soil pH throughout the incubation (Fig. 4a, and b). Soil pH decreased throughout the incubation with ash 60 and ash 45 being significantly higher than other treatments (Fig. 4a). At day 42 treatments, feedstock 60, biochars (350 and 650) dehydrated at 45 and 60, were below the control up to day 56. Soil pH generally decreased throughout the incubation period, with ash significantly higher than other treatments (Fig. 4b).

Discussion

The results from this study clearly show that the type of medium used during dehydration of urine significantly influenced nitrogen release patterns. Among pine bark products, those pyrolysed at higher temperatures, particularly biochar 650, showed the highest nitrogen recovery. This aligns with previous observations that high-temperature (500–600 °C) biochars possess superior adsorption capabilities due to increased aromaticity, porosity, and surface area[20]. In addition to the effects of pH and C/N ratio, the surface functional groups of the media also played an important role in nutrient retention. High temperature pyrolysis increases the development of internal pores, creating more adsorption sites for N rich products[20,21]. Based on the FTIR result these structural properties may have improved physical retention of urea during the dehydration process. Moreover, surface functional groups such as hydroxyl, carboxyl, and phenolic hydroxyl confirmed by FTIR analysis (Figure S2) likely facilitated chemical interactions through hydrogen bonding and complexation. These mechanisms may have contributed to the increased nitrogen stabilisation observed particularly in biochars.

The increase in ammonium-N concentration for the first 7 days (Fig. 1a, and b) could be the result of urea hydrolysis due to addition of moisture. Moisture is a significant factor that initiates urea hydrolysis process[22]. The findings also align with those of Kissel[23], where urea hydrolysis occurred within 4–7 days in warm temperature with optimum moisture content. Hydrolysis in soils is also influenced by pH, with the process generally increasing as pH rises with optimal pH range for urease enzyme activity being between 5.5 and 9[24]. When the pH exceeds 9, hydrolysis slows down[24]. At acidic pH ($pH < 7$) most of NH_3 will be converted to NH_4^+[25]. In the current study, all the treatment had pH that was less than 9 (Fig. 4a, and b).

The rapid decline in ammonium-N for all treatments from day 7 (Fig. 1a, and b), was attributed to nitrification, which was supported by the increase in nitrate-N. Furthermore, the increase in nitrate-N explains the decrease in pH (Fig. 4a, and b), as nitrification releases H^+ ions, which lower soil pH as observed by Sahrawat[26]. This aligns with the findings of Sigurdarson et al.[25], who observed a decrease in pH following urea application, attributed to nitrification. Nitrate -N was high in ash 45 (Fig. 2a), while the ash initially had no N (below detection) and it had 91% recovery of N from AHU (Table 2), which suggests that dissolution[27] and hydrolysis of urea occurred and all the ammonium-N was nitrified to nitrate-N. The urea might have remained free and ash is known to release all constituent nutrients to the soil upon application and stimulate microbial activities[28].

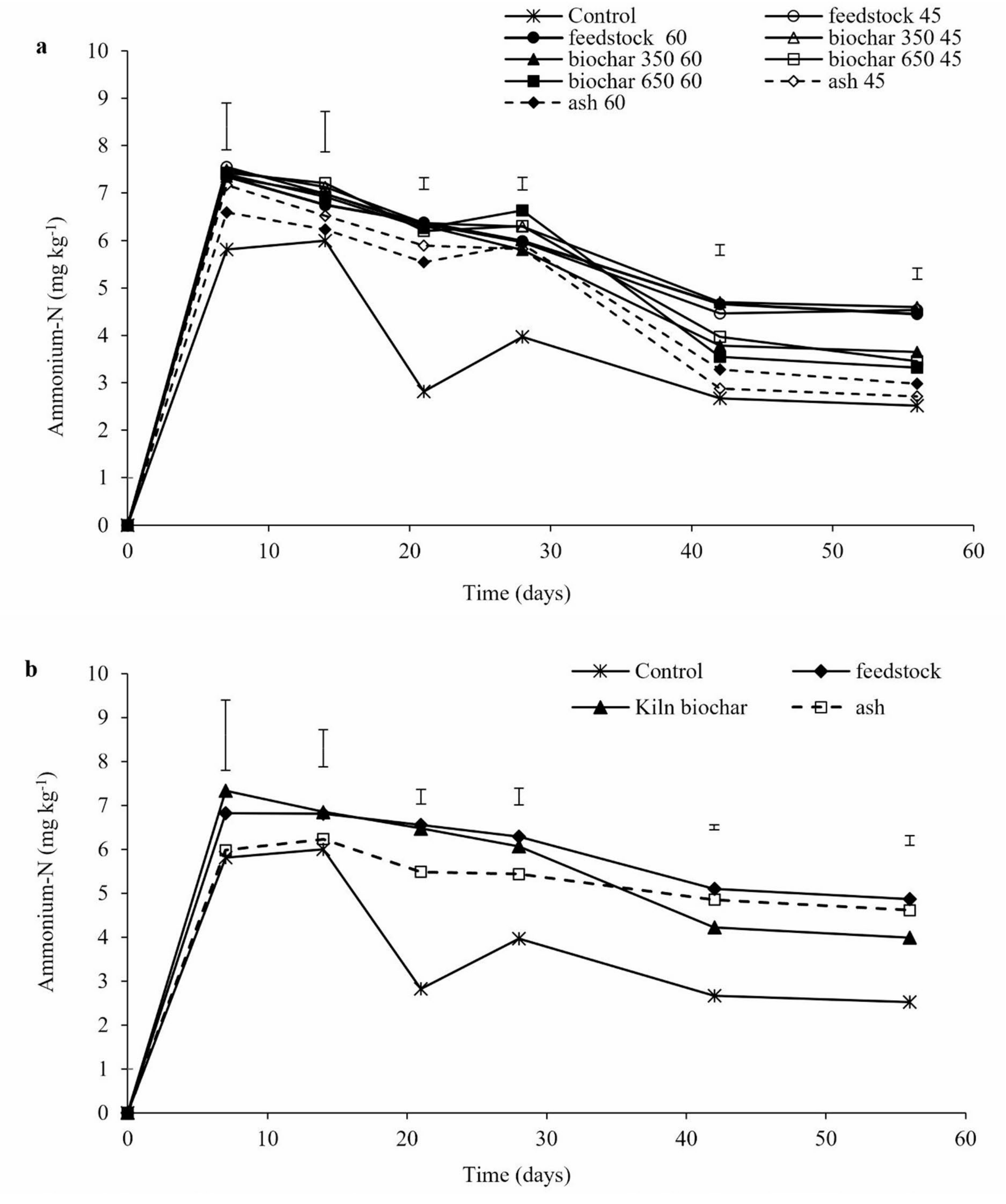

Fig. 1. Concentration of Ammonium-N released during incubation the products to soil in (**a**) experiment 1 (**b**) experiment 2. Feedstock 45 and feedstock 60- feedstock product dehydrated at 45 and 60 °C, respectively; ash 45 and ash 60- ash products dehydrated at 45 and 60 °C, respectively; biochar 350 45 and biochar 350 60- biochar at 350 °C dehydrated at 45 and 60 °C, respectively; biochar 650 45 and biochar 650 60-biochar at 650 °C dehydrated at 45 and 60 °C, respectively; feedstock G, kiln biochar G and ash G – feedstock, biochar from the kiln and ash, respectively, dehydrated in the glasshouse. The vertical error bars indicate LSD ($p < 0.05$).

The highest nitrate-N in the ash 45 (Fig. 2a) and ash G (Fig. 2b) treatments, which reached 37.2 and 38.7 mg kg^{-1} respectively, could supply an equivalent of 89.3 and 92.9 kg N ha^{-1} and less synthetic N will be required for optimum yield in spinach since it requires 100 kg N ha^{-1}. However, under field conditions the nitrate-N released could be lower due to fluctuations of soil moisture and temperature conditions[29]. The biochar (350 and 650 °C) products, dehydrated at 45 and 60 °C had significantly lower nitrate-N than other treatments, although they

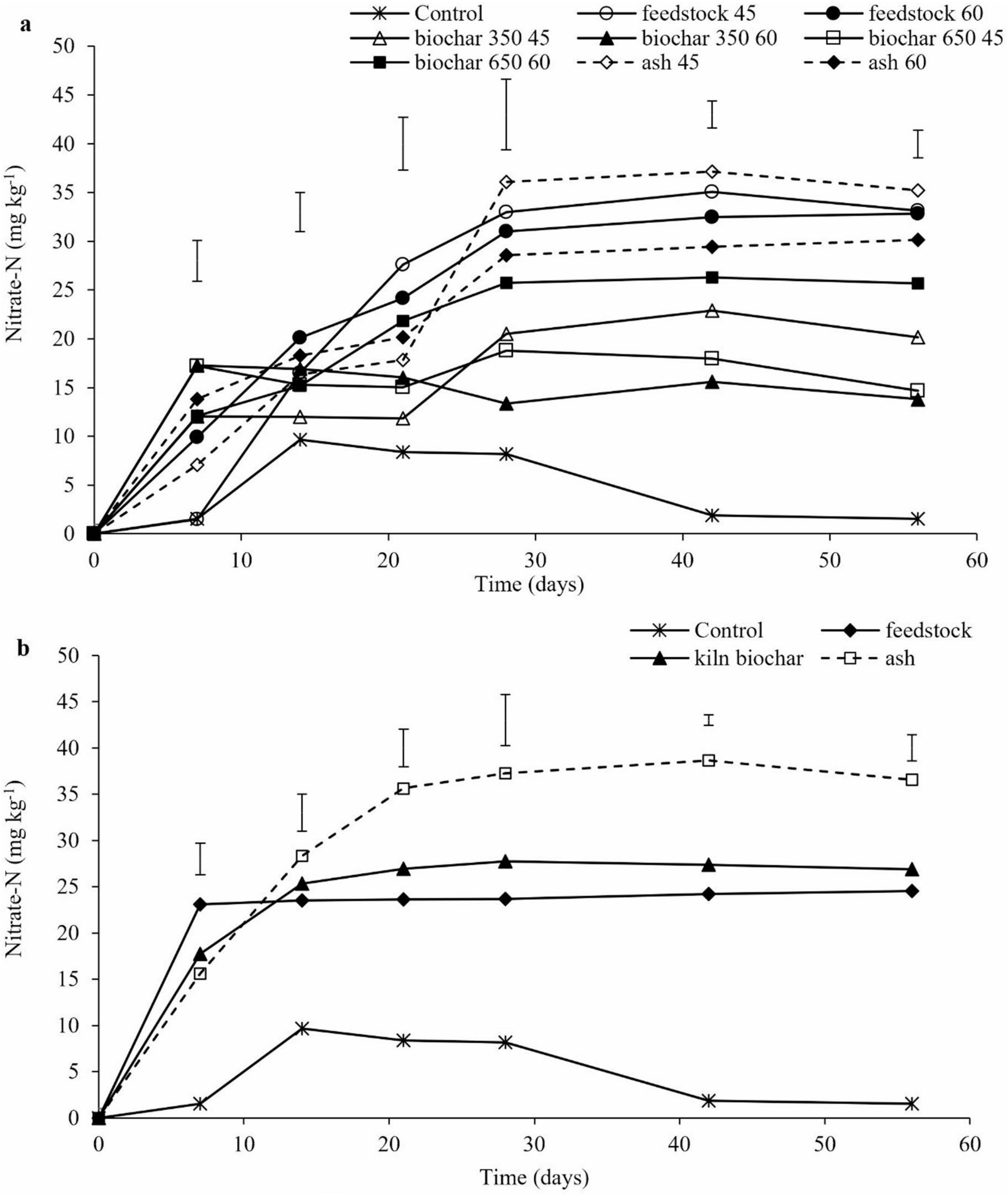

Fig. 2. Concentration of nitrate-N released during incubation the products to soil in (**a**) experiment 1 (**b**) experiment 2. Feedstock 45 and feedstock 60- feedstock product dehydrated at 45 and 60 °C, respectively; ash 45 and ash 60- ash products dehydrated at 45 and 60 °C, respectively; biochar 350 45 and biochar 350 60- biochar at 350 °C dehydrated at 45 and 60 °C, respectively; biochar 650 45 and biochar 650 60-biochar at 650 °C dehydrated at 45 and 60 °C, respectively; feedstock G, kiln biochar G and ash G – feedstock, biochar from the kiln and ash, respectively, dehydrated in the glasshouse. The vertical error bars indicate LSD ($p < 0.05$).

had a C/N less than 30, which would potentially support N mineralisation. The low nitrate-N may be due to the presence of stable carbon structures, such as aromatic rings, within the biochars, which could trap the urea, making it less accessible to the urease enzyme[30,31]. All the treatments had a C/N which is less than 30 (Table 2), and it is expected that mineralisation would be high in all the treatments. However, the mineralisation rate varied between treatments, indicating the differences in the ability of each urine product to release N into the

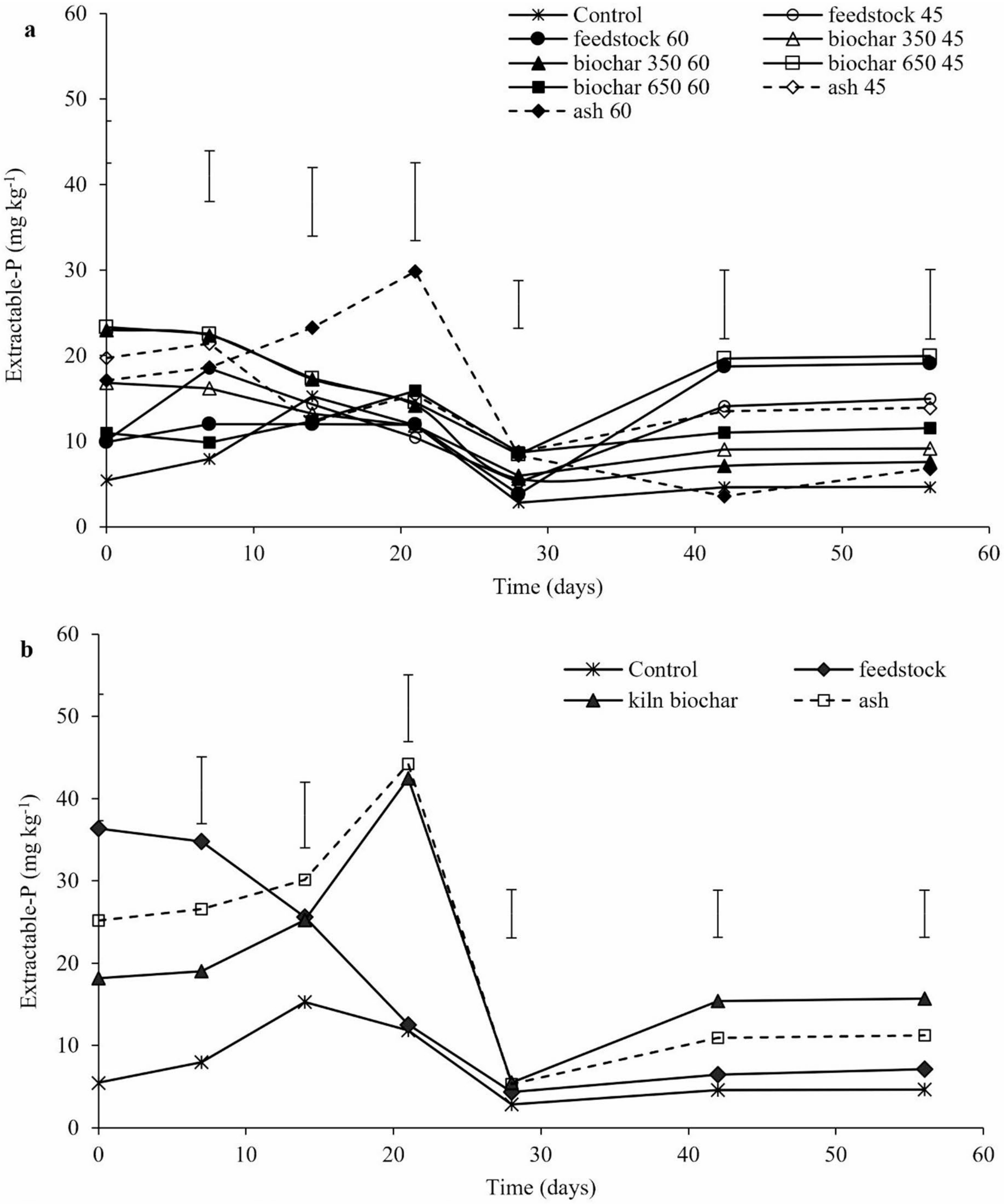

Fig. 3. Concentration of extractable-P released during incubation the products to soil in (**a**) experiment 1 (**b**) experiment 2. Feedstock 45 and feedstock 60- feedstock product dehydrated at 45 and 60 °C, respectively; ash 45 and ash 60- ash products dehydrated at 45 and 60 °C, respectively; biochar 350 45 and biochar 350 60- biochar at 350 °C dehydrated at 45 and 60 °C, respectively; biochar 650 45 and biochar 650 60-biochar at 650 °C dehydrated at 45 and 60 °C, respectively; feedstock G, kiln biochar G and ash G – feedstock, biochar from the kiln and ash, respectively, dehydrated in the glasshouse. The vertical error bars indicate LSD ($p < 0.05$).

soil. These differences can be attributed to variations in their functional groups, pore distribution, surface area, and chemical properties[32], including the liming effect of the materials.

The decrease in extractable-P at the beginning of the incubation until day 28, could be attributed to P fixation to the acidic sites. During the first 28 days, rapid nitrification (Fig. 2a and b) reduced soil pH, creating positively charged sites/colloids that increased P fixation. Pine bark feedstocks are acidic in nature and its decomposition

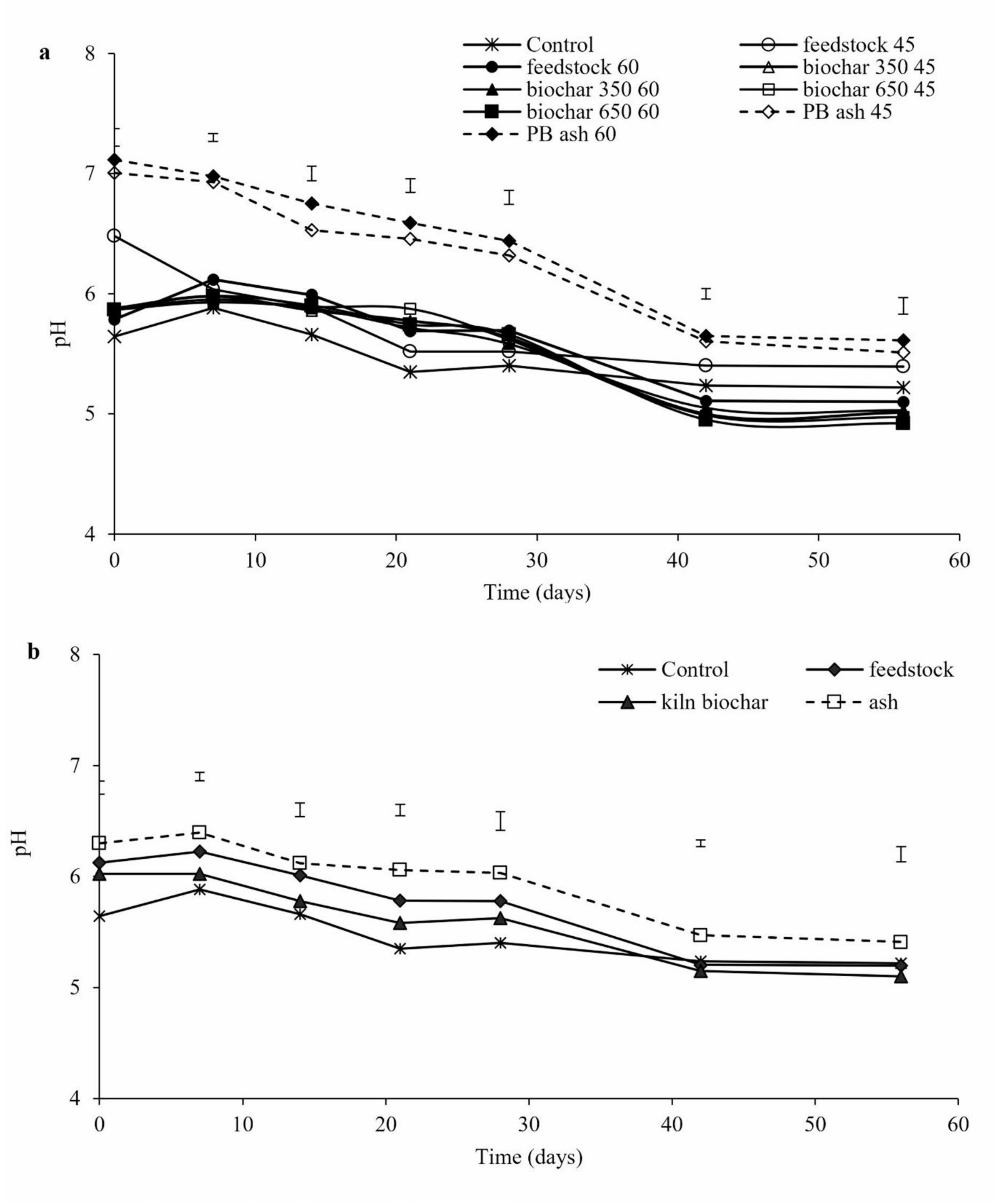

Fig. 4. Changes in soil pH during incubation the products to soil in (**a**) experiment 1 (**b**) experiment 2. Feedstock 45 and feedstock 60- feedstock product dehydrated at 45 and 60 °C, respectively; ash 45 and ash 60- ash products dehydrated at 45 and 60 °C, respectively; biochar 350 45 and biochar 350 60- biochar at 350 °C dehydrated at 45 and 60 °C, respectively; biochar 650 45 and biochar 650 60-biochar at 650 °C dehydrated at 45 and 60 °C, respectively; feedstock G, kiln biochar G and ash G – feedstock, biochar from the kiln and ash, respectively, dehydrated in the glasshouse. The vertical error bars indicate LSD ($p < 0.05$).

releases organic acids which might lower soil pH and adsorb the available P[33,34]. The decline of available P coincided with the declining pH (Fig. 4a and b). The sharp decline at day 28 could also be due to microbial immobilisation considering high N mineralisation in soil low in available P (3.86 mg kg^{-1}). The increase from day 28–42 could be explained by the release of the previously adsorbed P, and potential mineralisation of microbial P, thus causing an increase until day 42 and stabilise until day 56.

Dehydration temp (°C)	Urine Products	Recovered *N* as % of *N* in the urine added	pH	C (%)	*N* (%)	C: *N*
45	Feedstock	92.6^{cd}	6.93^{d}	38.8^{b}	2.23^{bc}	17.4^{b}
	Biochar 350	90.3^{cd}	6.64^{b}	43.2^{b}	2.50^{cd}	17.3^{b}
	Biochar 650	$*103^{de}$	6.74^{c}	62.5^{d}	2.25^{bc}	27.9^{c}
	Ash	90.5^{cd}	7.96^{f}	7.97^{a}	1.76^{ab}	4.56^{a}
60	Feedstock	85.4^{bc}	6.37^{a}	40.6^{b}	2.32^{bc}	17.5^{b}
	Biochar 350	89^{c}	6.64^{b}	53.6^{c}	2.63^{cd}	20.5^{b}
	Biochar 650	$*110^{e}$	6.74^{c}	80^{e}	2.97^{d}	27.1^{c}
	Ash	81^{bc}	7.92^{f}	7.3^{a}	1.79^{ab}	4.12^{a}
G	Feedstock	72.9^{ab}	6.40^{a}	36^{b}	2.19^{bc}	16.5^{b}
	Kiln biochar	81.5^{bc}	6.58^{b}	37.2^{b}	2.29^{bc}	16.3^{b}
	Ash	65.5^{a}	7.85^{e}	7.30^{a}	1.38^{a}	5.43^{a}

Table 2. Characteristics of dried urine-based products. * The recovered $N > 100\%$ as percentage of N added as urine, could have been caused by minor errors which may have accumulated. Values on the same column with different letters indicate significant differences ($p<0.05$). feedstock 45 and 60– feedstock dehydrated at 45 and 60 °C, respectively; ash 45 and ash 60– ash products dehydrated at 45 and 60 °C, respectively; biochar 350 45 and 350 60– biochar at 350 °C dehydrated at 45 and 60 °C, respectively; biochar 650 45 and 650 60– biochar at 650 °C dehydrated at 45 and 60 °C, respectively; feedstock G, kiln biochar G and ash G – feedstock, kiln biochar and ash, respectively, dehydrated in the glasshouse.

While the study provides new insights into nutrient release patterns from urine-based fertilisers derived from pine bark materials, the study was conducted under controlled conditions, which do not mimic field conditions, where temperature fluctuates together with wetting and drying conditions. Therefore, further studies should be done under field conditions. The study also looked at nitrogen ad phosphorous release patterns only and including other important parameters such as micronutrients, potassium, carbon emission and microbial enzyme activity could have solidified the work and need to be considered for future work.

Conclusion

The study showed that at a similar nitrogen rate, both ash dehydrated at 45 °C and ash dehydrated at the glasshouse resulted in higher nitrate-N levels. This suggests that ash enriched with urine could serve as a nitrogen source, potentially reducing the need for synthetic nitrogen fertilisers. Soil pH significantly influenced urea hydrolysis, while the properties of the media (functional groups) also affected nitrogen release. No differences in ammonium and nitrate-N were observed among the biochar-urine products in this study. Overall, the findings suggest that pine bark products could enhance soil fertility. Future research should explore the effects of urine-based products on crop growth in both controlled and field settings.

Data availability

The datasets used for graphs and table are available from the corresponding author upon request.

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Author contributions

P. Muchaonyerwa conceived the idea for the study, supervised the design, data collection, and analysis, and assisted in revising the manuscript. A.O. Odindo contributed to reviewing, editing, and validation. S.P. Vilakazi co-conceived the study, designed and performed the experiments, conducted data collection and analysis, and wrote the first draft of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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