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Catalytic pyrolysis of chicken bone waste with potassium tartrate: availability of macro- and micronutrients

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Abstract: Biochar derived from bone waste (bone char) is a promising phosphorus fertiliser. However, limited nutrient availability restricts its agricultural application; therefore, different amendments have been investigated to modify nutrient release from biochar. This study evaluated the effects of pyrolysis temperature and the addition of potassium tartrate (KTar) as an *in-situ* catalyst on the water solubility of selected macro- and micronutrients in chicken bone waste-derived bone char. Chicken bone waste (CBW) was mixed with KTar at a 10:1 mass ratio and pyrolysed at 400–800 °C for 30 min. The KTar modification strongly affected nutrient retention and extractability. In particular, KTar enhanced sulphur retention at temperatures above 400 °C, resulting in total sulphur contents 55–97% higher than those in unmodified bone chars, and promoted almost complete water extractability of sulphur at 400 °C. Phosphorus availability was also increased by KTar. The extractable-to-total phosphorus ratios were 6 times higher at 400 °C and 1.7–2.5 times higher at higher temperatures compared with unmodified bone chars. In addition, KTar altered micronutrient behaviour as it increased the availability of iron and copper, likely through the formation of soluble salts, promoted zinc volatilisation at 800 °C and enhanced the extractability of the remaining zinc fraction. Overall, KTar modification improved the fertilising potential of bone chars by increasing the water-extractable fractions of essential nutrients. Specifically, KTar-modified bone char obtained at 500 °C represents the optimal treatment, with a balanced high yield, carbon stability, and water-extractable phosphorus, sulfur, iron, and copper. These findings suggest that KTar-assisted pyrolysis is a promising strategy for producing nutrient-enriched bone chars for agricultural applications.

Keywords: chicken meat-bone waste; poultry industry; plant nutrient; water-extractable content; waste stabilisation; phosphorus recycling; plant availability

Increasing global meat production has resulted in a significant increase in waste from the poultry industry. Chicken bone waste (CBW), a by-product composed mainly of bones, fat and residual meat, represents an essential source of nutrients that can be recycled through thermal conversion. Among available processing methods, pyrolysis is considered an efficient and safe technique for waste stabilisation and nutrient recovery, producing carbon-rich materials such as bone char with potential agricultural value (Hart et al. 2022).

Bone char contains large amounts of essential plant nutrients, especially P, Ca and Mg (Leinweber et al. 2019). These elements are vital for soil fertility and crop production, particularly in acidic soils where bone char application can also increase pH, cation exchange capacity and nutrient retention (Ahmed et al. 2021). Phosphorus (P) is a key macronutrient required for plant growth, and its natural reserves are limited. Phosphate rock, the main raw material for mineral P fertilisers, is listed by the European

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Commission as a Critical Raw Material due to its non-renewable nature and concentrated supply. Recycling P from animal by-products such as bone residues could therefore contribute to a more sustainable nutrient cycle and reduce dependence on conventional mineral fertilisers (Hart et al. 2022).

However, most phosphorus in bone char is bound in the form of hydroxyapatite, which is poorly soluble in water and thus not readily available to plants. Pyrolysis conditions strongly influence the solubility and availability of nutrients. Higher temperatures usually promote the formation of stable Ca-P minerals, decreasing P availability. On the other hand, chemical modification of the feedstock before pyrolysis can alter the final product composition and enhance nutrient release (Xia et al. 2020, Buss et al. 2022, Frišták et al. 2022, Taisheva et al. 2026).

Several studies have shown that the addition of potassium (K) compounds affects the physicochemical properties of biochar and promotes the formation of more soluble K phosphates (Buss et al. 2020, Chen et al. 2020a, Tu et al. 2021, Buss et al. 2022). The presence of K may also influence the extractability of other nutrients, such as Mg, Fe and Zn; however, these potential effects are not yet well understood and remain insufficiently studied. Additionally, K additives can interact with sulphur (S) during thermal degradation of organic matter, influencing S release and retention in the solid phase (Lin et al. 2017, Braidy et al. 2023). Potassium tartrate – $K_2C_4H_4O_6$ (KTar) is an organic potassium salt that could act as a catalyst during pyrolysis and modify nutrient transformations, but its effects on bone char composition have not yet been evaluated.

The study focuses on the potential agricultural use of the bone chars as a renewable source of essential plant nutrients. We hypothesised that KTar addition would act as an *in-situ* catalyst during CBW pyrolysis, influencing water-extractable macro- and micronutrient fractions in bone chars, and that this process would be governed by pyrolysis temperature.

To test this hypothesis, the aim of this study was to determine the impact of pyrolysis temperature and KTar addition on the total and water-extractable contents of selected macro- (Ca, Mg, K, P, S) and micronutrients (Cu, Fe, Mn, Zn) in chicken bone waste.

MATERIAL AND METHODS

Bone char preparation. Bone chars were produced by pyrolysis of CBW and a CBW-KTar (10:1 w/w)

mixture at temperatures ranging from 400 to 800 °C, with a 30-min residence time. This mixing ratio is equivalent to an added pure K (from KTar) loading of 3.14 wt.%, which falls directly within the economically feasible and technologically manageable low-dose catalytic regime identified in several biochar studies (Masek et al. 2019, Fan et al. 2021, Buss et al. 2022) rather than high-loading activation processes. Obtained bone chars were denoted as BC-X for plain bone char and BCKTar-X for bone chars from KTar-impregnated feedstock, where X is substituted by pyrolysis temperature. An electric laboratory tube furnace (GHA 12/600, Carbolite Gero Ltd., Hope, UK) was used for the pyrolysis. The process was similar to that described by Mercl et al. (2020) and Taisheva et al. (2026). Before pyrolysis, the dried CBW was milled and passed through a 2-mm stainless-steel sieve.

Analytical methods. For the total elemental analysis, 0.3 g of CBW and bone char samples were digested with HNO_3 , HF, and *aqua regia* after the dry-ashing procedure (Ulloa-Murillo et al. 2026). Samples were then diluted to a final volume of 25 mL with demineralised water and analysed by ICP-OES (Agilent 720, Agilent Technologies Inc., Santa Clara, USA).

The content of available macro- and micronutrients in untreated CBW and in the mixtures after pyrolysis was determined by ICP-OES following the deionised water extraction (1:100 w/v ratio) procedure described by Buss et al. (2018).

The samples' pH was measured in a 1:5 (w/v) suspension with 0.01 mol/L $CaCl_2$ after 2 h of shaking and 1 h of settling, using a WTW pH 340i meter with a glass electrode (WTW, Weilheim, Germany).

Statistical analysis. A one-way ANOVA was used to determine the effects of temperature on the properties of the bone chars obtained. Statistically significant differences (Fisher's least significant difference (LSD) test) are shown at the 95% confidence level. A *t*-test was used to evaluate differences between BC and BCKTar. Principal component analysis (PCA) was performed on the extractable-to-total ratios of nutrients. Analysis was run using OriginPro 2023b (OriginLab Corporation, Northampton, USA).

RESULTS AND DISCUSSION

Chicken bone waste and bone char characteristics. Selected properties of CBW and bone chars are presented in Table 1. Overall, the bone char yield decreased with increasing temperature – from

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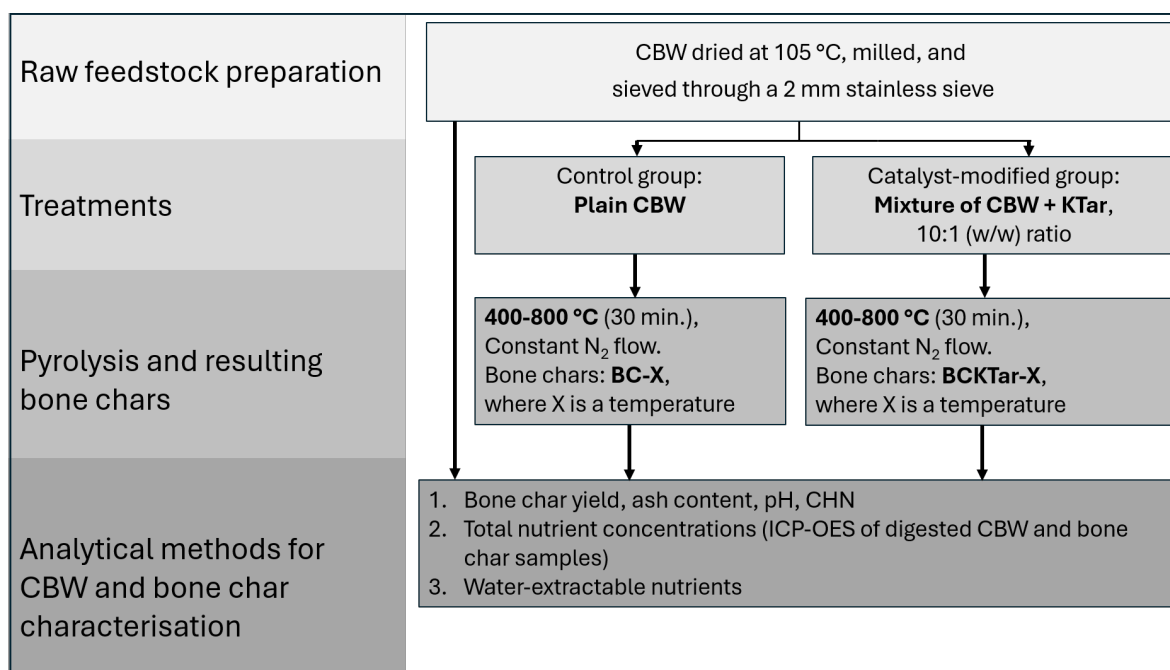


Figure 1. A schematic diagram of the experimental design

~43–44 wt.% at 400 °C to 35–36 wt.% at 800 °C for CBW due to temperature-induced loss of C, H, and N. Notably, the presence of KTar in the feedstock had a negligible influence on the overall bone char yield across the examined temperature range.

Pyrolysis caused a marked increase in the pH of the resulting bone chars. The presence of KTar in the feedstock further enhanced the alkalinity of the bone chars produced at 400–600 °C. However, at higher temperatures (700–800 °C), the pH values of both treatments almost converged, with pH ~10.5–11.5. The increase in pH of the bone chars is most likely attributed to the higher ash content generated during pyrolysis. It may also suggest a reduction in oxygen-containing surface groups on the bone char, accompanied by their replacement with neutral or basic aromatic groups (Alkurdi et al. 2020).

The total content of nutrients

Macronutrients. The total contents of macronutrients in raw CBW and bone chars are shown in Table 2. Since hydroxyapatite is a main bone component, the most abundant elements in the raw CBW are Ca and P with ~104 and ~51 g/kg. N also has a high content of ~72 g/kg (Table 1) due to the high protein content of meat bone waste (Choi et al. 2021). K, Mg, and S are present in much smaller amounts (~6 g/kg for K and ~2 g/kg for Mg and S), consistent with

studies by Cascarosa et al. (2011) and Fristak et al. (2019). Pyrolysis at 400–800 °C led to the elevated concentration of all macronutrients except N for both feedstocks and S for CBW pyrolysis.

As shown in Table 1, degradation and volatilisation of N-containing components of CBW begin at 400 °C, consistent with Feng et al. (2018) below. As the pyrolysis temperature increased, the N content declined for both BCs and BCKTars.

Our results (Table 2) also suggest that S volatilises during the pyrolysis of plain CBW. This is consistent with Kantorek et al. (2019), who reported the volatilisation of S as H₂S at temperatures above 300 °C. The pyrolysis of K-modified feedstock at 500–800 °C resulted in bone char with 55–97% higher S content than BCs, and this content was not significantly different from that in raw CBW. The reduced bone char yield with temperature rise implies S enrichment in the solid phase. Although K is well known as a catalyst for protein degradation (Guo et al. 2024), a finding consistent with the N loss observed in our study, it influences S behaviour differently. The observed S fixation in BCKTars following CBW and KTar mixture pyrolysis aligns with previously reported results using KOH (Lin et al. 2017), K₂FeO₄ (Zhang et al. 2023), and inherent K compounds (Braidly et al. 2023). These studies have similarly shown reduced S volatilisation and enhanced solid-phase retention during pyrolysis of oily sludge, sewage sludge, and

Table 1. Selected properties of untreated chicken bone waste (CBW) and bone char samples

T (°C)	Material	Yield	pH	Ash	C _{tot}	H _{tot}	N _{tot}	O ^x	H/C AR ^y
(wt. %)									
105	CBW	–	5.5 ± 0.0 ^{eF}	28.6 ± 0.23 ^{fF}	40.1 ± 0.32 ^{aA}	7.68 ± 0.22 ^{aA}	7.15 ± 0.08 ^{aA}	22.5 ± 0.5 ^{aA}	2.30 ± 0.08 ^{aA}
400	BC	43.6 ± 1.2 ^a	8.6 ± 0.0 ^{d***}	60.8 ± 0.1 ^{e***}	26.1 ± 0.1 ^b	2.39 ± 0.06 ^b	4.42 ± 0.04 ^{b*}	15.0 ± 0.3 ^{b***}	1.10 ± 0.03 ^b
	BCKTar	43.1 ± 0.8 ^A	11.6 ± 0.0 ^C	63.3 ± 0.1 ^E	25.9 ± 0.1 ^B	2.47 ± 0.10 ^B	3.74 ± 0.10 ^B	11.9 ± 0.1 ^C	1.15 ± 0.05 ^B
500	BC	37.6 ± 0.2 ^{b*}	10.4 ± 0.0 ^{c***}	70.3 ± 0.2 ^d	19.9 ± 0.1 ^{c*}	1.40 ± 0.04 ^c	3.50 ± 0.03 ^{c*}	15.1 ± 0.5 ^{c*}	0.84 ± 0.02 ^c
	BCKTar	38.3 ± 0.3 ^B	12.3 ± 0.0 ^A	70.9 ± 0.3 ^D	20.4 ± 0.0 ^C	1.41 ± 0.03 ^C	3.34 ± 0.01 ^C	12.4 ± 0.4 ^C	0.83 ± 0.02 ^C
600	BC	36.9 ^{b***} ± 0.2	10.7 ± 0.0 ^{b***}	72.6 ± 0.0 ^{c*}	18.5 ± 0.2 ^d	0.98 ± 0.02 ^d	2.81 ± 0.01 ^d	17.5 ± 0.7 ^c	0.64 ± 0.01 ^d
	BCKTar	37.7 ± 0.2 ^B	12.1 ± 0.0 ^B	72.8 ± 0.2 ^C	18.8 ± 0.2 ^D	0.92 ± 0.01 ^D	2.93 ± 0.04 ^D	15.1 ± 1.1 ^B	0.59 ± 0.01 ^D
700	BC	35.7 ± 0.1 ^c	10.9 ± 0.2 ^{a**}	74.6 ± 0.0 ^b	18.2 ± 0.1 ^d	0.65 ± 0.00 ^{e**}	2.65 ± 0.04 ^{e*}	14.6 ± 0.3 ^c	0.43 ± 0.00 ^{e*}
	BCKTar	36.0 ± 0.3 ^C	11.6 ± 0.1 ^D	74.7 ± 0.1 ^B	18.5 ± 0.2 ^D	0.72 ± 0.01 ^{DE}	2.86 ± 0.02 ^D	11.3 ± 1.3 ^C	0.46 ± 0.01 ^E
800	BC	35.5 ± 0.3 ^c	11.1 ± 0.1 ^{a**}	76.4 ± 0.1 ^a	17.2 ± 0.2 ^e	0.48 ± 0.02 ^{e*}	2.60 ± 0.04 ^e	13.1 ± 0.5 ^{d*}	0.34 ± 0.01 ^{f*}
	BCKTar	35.1 ± 0.5 ^C	10.4 ± 0.0 ^E	77.0 ± 0.2 ^A	17.7 ± 0.1 ^E	0.58 ± 0.00 ^E	2.50 ± 0.01 ^E	8.3 ± 0.9 ^D	0.40 ± 0.00 ^E

Values are presented as the arithmetic mean ($n = 2$) ± standard deviation; ^xdry, ash-free basis (_{daf}), calculated as $O = 100 - H_{daf} - C_{daf} - N_{daf} - S_{daf}$, ^yatomic ratio. T stands for pyrolysis temperature (30 min). Results of CBW and BC (bone chars prepared from plain CBW) were presented by Taisheva et al. (2026). Means which do not share letters (within data for each property) are significantly different across temperatures ($P \leq 0.05$, 1-way ANOVA, and Fisher's *LSD* test were performed independently for each feedstock type. BC and BCKTar (bone chars prepared from CBW treated with KTar) treatment data are marked with lowercase or uppercase letters, respectively); *, **, and *** indicate significant differences between the BC and BCKTar for given temperature (*t*-test; $P \leq 0.05$, 0.01, and 0.001, respectively)

corn residues, respectively. K salts can react with S-containing intermediates (e.g., H_2S , SO_2 , thiols) of protein degradation to form thermally stable sulphates (Braidly et al. 2023) or sulphides (Chen et al. 2020b, Xu et al. 2026) within the char matrix. However, K can also play an opposite role in the transformation of S during pyrolysis, acting as a catalyst for S volatilisation (Sugawara et al. 1995, Lin et al. 2017, Xu et al. 2026). These contradictory behaviours are primarily governed by the specific chemical form of the K additive, the feedstock composition, and the pyrolysis temperature.

Micronutrients. The content of micronutrients in raw CBW and bone chars is shown in Table 3. One can see that the Cu and Mn contents in CBW are very low (~2–4 mg/kg) compared to other micronutrients. Fristak et al. (2019) reported a 10-fold

higher Fe content in bone meal and similar values for Zn. The content of micronutrients in bone chars is comparable with pig bone chars (Dela Piccola et al. 2021), yet the Mn content is ~6 times lower than that reported by Park et al. (2019) for chicken bone biochar.

Increasing temperature led to an increase in Zn content in BCs up to 600–700 °C. Zielińska and Oleszczuk (2015) reported an increase in Zn content during the pyrolysis of sewage sludge up to 600 °C, followed by a reduction at 700 °C. This behaviour of Zn can indicate partial devolatilisation at elevated temperatures (Hossain et al. 2011). Pyrolysis at 800 °C decreased Zn content in bone char samples, especially in BCKTars. The Zn content in BCKTar-800 was 33 mg/kg, which is approximately 3 times lower than in untreated CBW. Hence, the presence of KTar in

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Table 2. The total, water-extractable content (g/kg) of macronutrients in chicken bone waste (CBW), bone chars prepared from plain CBW (BCs) and bone chars prepared from CBW treated with KTar (BCKTars)

	CBW	400 °C		500 °C		600 °C		700 °C		800 °C	
		BC	BC KTar	BC	BC KTar	BC	BC KTar	BC	BC KTar	BC	BC KTar
Ca _{total}	104 ± 3 ^{cB}	187 ± 11 ^{a*}	152 ± 1 ^A	160 ± 10 ^{ab}	152 ± 14 ^A	174 ± 14 ^{ab}	172 ± 6 ^A	167 ± 15 ^{ab}	159 ± 2 ^A	151 ± 9 ^b	163 ± 26 ^A
Ca _{ext}	3.10 ± 0.18 ^{aA}	0.41 ± 0.20 ^b	0.34 ± 0.03 ^B	0.47 ± 0.02 ^{b*}	0.32 ± 0.04 ^B	0.25 ± 0.08 ^b	0.26 ± 0.01 ^B	0.28 ± 0.01 ^b	0.25 ± 0.00 ^B	0.31 ± 0.04 ^b	0.38 ± 0.10 ^B
K _{total}	6.06 ± 0.14 ^{bD}	14.1 ± 0.8 ^{a**}	50.5 ± 2.7 ^C	16.0 ± 2.7 ^{a**}	57.6 ± 1.4 ^{AB}	16.1 ± 1.1 ^{a**}	60.1 ± 2.9 ^A	16.1 ± 0.5 ^{a***}	59.6 ± 1.7 ^{AB}	16.4 ± 1.2 ^{a***}	55.3 ± 0.5 ^B
K _{ext}	5.30 ± 0.02 ^{dD}	3.86 ± 0.90 ^{e***}	27.8 ± 1.0 ^C	7.27 ± 0.47 ^{c***}	35.9 ± 0.3 ^B	8.57 ± 0.01 ^{bc***}	36.9 ± 1.1 ^B	9.52 ± 0.21 ^{ab***}	44.6 ± 0.4 ^A	10.4 ± 0.3 ^{a***}	44.6 ± 0.4 ^A
Mg _{total}	2.28 ± 0.04 ^{cC}	5.00 ± 0.03 ^{b*}	4.19 ± 0.26 ^B	5.42 ± 0.38 ^{ab}	4.62 ± 0.16 ^A	5.57 ± 0.03 ^{a**}	4.74 ± 0.10 ^A	5.54 ± 0.26 ^{a*}	4.58 ± 0.06 ^A	5.86 ± 0.20 ^{a*}	4.76 ± 0.12 ^A
Mg _{ext}	0.81 ± 0.05 ^{aA}	0.09 ± 0.02 ^b	0.13 ± 0.03 ^{BC}	0.11 ± 0.00 ^b	0.10 ± 0.01 ^C	0.06 ± 0.01 ^{b*}	0.12 ± 0.01 ^{BC}	0.11 ± 0.01 ^{b*}	0.14 ± 0.00 ^{BC}	0.11 ± 0.01 ^b	0.19 ± 0.06 ^B
P _{total}	50.8 ± 1.6 ^{dC}	110 ± 1 ^c	104 ± 3 ^B	124 ± 9 ^b	119 ± 11 ^{AB}	128 ± 1 ^{ab}	120 ± 6 ^{AB}	128 ± 4 ^{ab}	121 ± 9 ^{AB}	137 ± 8 ^a	122 ± 8 ^A
P _{ext}	3.63 ± 0.27 ^{aB}	0.44 ± 0.06 ^{d***}	2.43 ± 0.07 ^C	1.49 ± 0.18 ^{c**}	3.37 ± 0.01 ^B	2.22 ± 0.02 ^{b*}	3.72 ± 0.23 ^B	2.26 ± 0.05 ^{b***}	4.48 ± 0.07 ^A	1.63 ± 0.08 ^{c**}	3.72 ± 0.08 ^B
S _{total}	2.33 ± 0.15 ^{bA}	2.86 ± 0.10 ^a	2.50 ± 0.24 ^A	1.80 ± 0.11 ^{c*}	2.44 ± 0.17 ^A	1.42 ± 0.14 ^{d*}	2.61 ± 0.20 ^A	1.66 ± 0.00 ^{cd**}	2.58 ± 0.10 ^A	1.41 ± 0.06 ^{d*}	2.78 ± 0.36 ^A
S _{ext}	2.00 ± 0.06 ^{aC}	0.67 ± 0.02 ^{c***}	2.51 ± 0.10 ^A	1.01 ± 0.02 ^{b***}	2.20 ± 0.02 ^B	0.40 ± 0.03 ^{d**}	1.28 ± 0.03 ^D	0.05 ± 0.00 ^{e***}	0.50 ± 0.01 ^E	0.06 ± 0.00 ^{e**}	0.28 ± 0.02 ^F

Data are presented as the arithmetic mean ($n = 2$) ± standard deviation. Total contents were determined after digestion with HF + HNO₃ and *aqua regia* (Ulloa-Murillo et al. 2026). Water-extractable (_{ext}) contents were measured after extraction by demineralised water (1:100 w/v). Means which do not share letters (within data for each element) are significantly different across temperatures ($P \leq 0.05$, 1-way ANOVA, and Fisher's *LSD* test were performed independently for each feedstock type. BC and BCKTar treatment data are marked with lowercase or uppercase letters, respectively); *, **, and *** indicate significant differences between the BC and BCKTar for given temperature (*t*-test; $P \leq 0.05$, 0.01, and 0.001, respectively)

the feedstock can influence Zn volatilisation during pyrolysis.

Availability of nutrients. While the total element content is critical to the bone char's potential as a fertiliser, the most important factor is nutrient availability. Deionised water extraction is one method used to measure the plant-available P content in recycled products (Brod et al. 2015, Buss et al. 2020). While Kratz et al. (2010) reported the strongest correlation between short-term plant P uptake and water-soluble P, the latter characterises the most readily labile fractions and is not an indicator of the complex chemical and biological processes governing nutrient availability in soils.

Effect of pyrolysis temperature. In the raw CBW, K and S showed the highest extractable ratios (87.6% and 85.9%), followed by Mg (35.3%) and P (7.15%),

whereas Ca was least available (2.99%) (Figure 2). Pyrolysis at 400 °C sharply reduced nutrient extractability in BCs, with K and S decreasing to 27.4% and 23.6%, and Ca, Mg, and P dropping to 0.22, 1.74, and 0.4%, respectively. A decline in water-soluble P during pyrolysis has been reported for various feedstocks, including crop residues (Xu et al. 2016), manure (Cantrell et al. 2012), and sheep, chicken, and pig bones (Ahmed et al. 2021). Zwetsloot et al. (2015) suggested that P solubility in water is associated with CaP crystallinity, which increases with pyrolysis temperature. Similarly, Dela Piccola et al. (2021) attributed this increase in crystallinity to enhanced symmetry within P compounds formed during thermal treatment.

Increasing the temperature to 800 °C had no perceptible influence on the extractable ratios of Ca and Mg,

Table 3. The total, water-extractable content (mg/kg) of micronutrients in chicken bone waste (CBW), bone chars prepared from plain CBW (BCs) and bone chars prepared from CBW treated with KTar (BCKTars)

	CBW	400 °C		500 °C		600 °C		700 °C		800 °C	
		BC	BC KTar	BC	BC KTar	BC	BC KTar	BC	BC KTar	BC	BC KTar
Cu _{total}	4.01 ± 1.21 ^{aC}	3.85 ± 0.45 ^a	4.58 ± 0.38 ^{ABC}	5.87 ± 1.31 ^a	4.21 ± 1.36 ^{BC}	5.65 ± 1.24 ^a	7.06 ± 0.95 ^{AB}	6.49 ± 2.52 ^a	6.23 ± 0.84 ^{ABC}	6.37 ± 2.14 ^a	7.33 ± 1.82 ^A
Cu _{ext}	< 0.50	< 0.50	< 0.50	< 0.50 ^{**}	1.13 ± 0.05 ^B	< 0.50 [*]	1.44 ± 0.21 ^{AB}	< 0.50 [*]	1.77 ± 0.34 ^A	< 0.50 [*]	1.22 ± 0.22 ^B
Fe _{total}	57 ± 3 ^{bB}	147 ± 0 ^a	95 ± 28 ^{AB}	153 ± 12 ^{a*}	104 ± 8 ^{AB}	141 ± 0 ^a	105 ± 24 ^{AB}	141 ± 5 ^a	137 ± 53 ^A	140 ± 11 ^a	126 ± 16 ^A
Fe _{ext}	1.24 ± 0.06	0.13 ± 0.25 ^{***}	2.31 ± 0.04	< 0.50 ^{***}	2.63 ± 0.02	< 0.50 ^{**}	1.37 ± 0.18	< 0.50 ^{**}	4.44 ± 0.26	1.44 ± 0.06 ^{***}	13.40 ± 0.02
Mn _{total}	2.25 ± 0.16 ^{aA}	4.84 ± 0.07 ^a	5.34 ± 3.30 ^A	5.26 ± 0.36 ^a	4.51 ± 0.60 ^A	5.43 ± 0.08 ^a	4.37 ± 0.63 ^A	5.41 ± 0.38 ^a	5.16 ± 1.28 ^A	6.06 ± 0.28 ^a	5.22 ± 0.55 ^A
Mn _{ext}	0.67 ± 0.02 ^{aA}	0.09 ± 0.07 ^{bc}	< 0.10	0.16 ± 0.05 ^b	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Zn _{total}	111 ± 10 ^{cB}	243 ± 37 ^{ab}	222 ± 28 ^A	271 ± 28 ^a	253 ± 16 ^A	281 ± 39 ^a	248 ± 27 ^A	279 ± 47 ^a	219 ± 16 ^A	193 ± 10 ^{b**}	33 ± 1 ^C
Zn _{ext}	1.39 ± 0.15 ^{aC}	0.97 ± 0.31 ^{b**}	2.55 ± 0.06 ^A	0.56 ± 0.03 ^{c**}	1.50 ± 0.04 ^{BC}	< 0.20	0.10 ± 0.13 ^D	< 0.20 ^{**}	2.04 ± 0.18 ^{AB}	< 0.20 [*]	1.51 ± 0.57 ^{BC}

Data are presented as the arithmetic mean ($n = 2$) ± standard deviation. Total contents were determined after digestion with HF + HNO₃ and *aqua regia* (Ulloa-Murillo et al. 2026). Water-extractable (ext) contents were measured after extraction by demineralised water (1:100 w/v). Means which do not share letters (within data for each element) are significantly different across temperatures ($P \leq 0.05$, 1-way ANOVA, and Fisher's *LSD* test were performed independently for each feedstock type. BC and BCKTar treatment data are marked with lowercase or uppercase letters, respectively); *, **, and *** indicate significant differences between the BC and BCKTar for given temperature (*t*-test; $P \leq 0.05$, 0.01, and 0.001, respectively)

suggesting that these elements remained largely bound within stable mineral phases throughout the thermal treatment. In contrast, the extractable fraction of K increased significantly from 27.4% to 63.4% between 400 °C and 800 °C. This finding is consistent with the results of Ippolito et al. (2015) and Buss et al. (2016), who reported high K availability (up to 100%) across various biochars and extraction methods.

Conversely, the proportion of water-extractable S peaked at 56.1% at 500 °C, then decreased by nearly half at 600 °C and declined sharply to approximately 3–4% at 700–800 °C. This behaviour suggests the formation of thermally stable, less soluble S compounds at higher pyrolysis temperatures.

Among the micronutrients, Mn was the most water-extractable in CBW, with an Mn_{ext}/Mn_{total} ratio of 29.8% (Figure 3C). In contrast, only ~1–2% of total Fe and Zn were water-extractable, while Cu levels were below the instrument's quantification limit (0.5 mg/kg).

As shown in Figure 3, thermal treatment of CBW reduced the water-extractable fractions of all micro-

nutrients compared with the untreated material. He et al. (2010) reported a similar trend, with water-soluble Cu and Zn decreasing sharply at temperatures above 350 °C, suggesting that pyrolysis enhances the stability of these metals. Likewise, Gunes et al. (2015) observed a decline in the water-soluble-to-total ratios of Fe, Zn, Cu, and Mn following the pyrolysis of poultry manure. The PCA biplot (Figure 4) supports these findings, with BC samples clustering tightly at negative PC1 scores, reflecting their uniformly low extractability across all pyrolysis temperatures.

KTar effect. Pyrolysis of the KTar-modified feedstock enhanced the availability of all macronutrients except Ca. In particular, almost all of the total S was water-extractable in BCKTar-400, which is four times higher than in BC-400, supporting the hypothesis that K and S can form water-soluble salts during pyrolysis, with part of the S retained in bone char structures. As the pyrolysis temperature increased, S availability declined sharply to ~10% at 800 °C, indicating the formation of stable and immobile S compounds. The extractable K fraction

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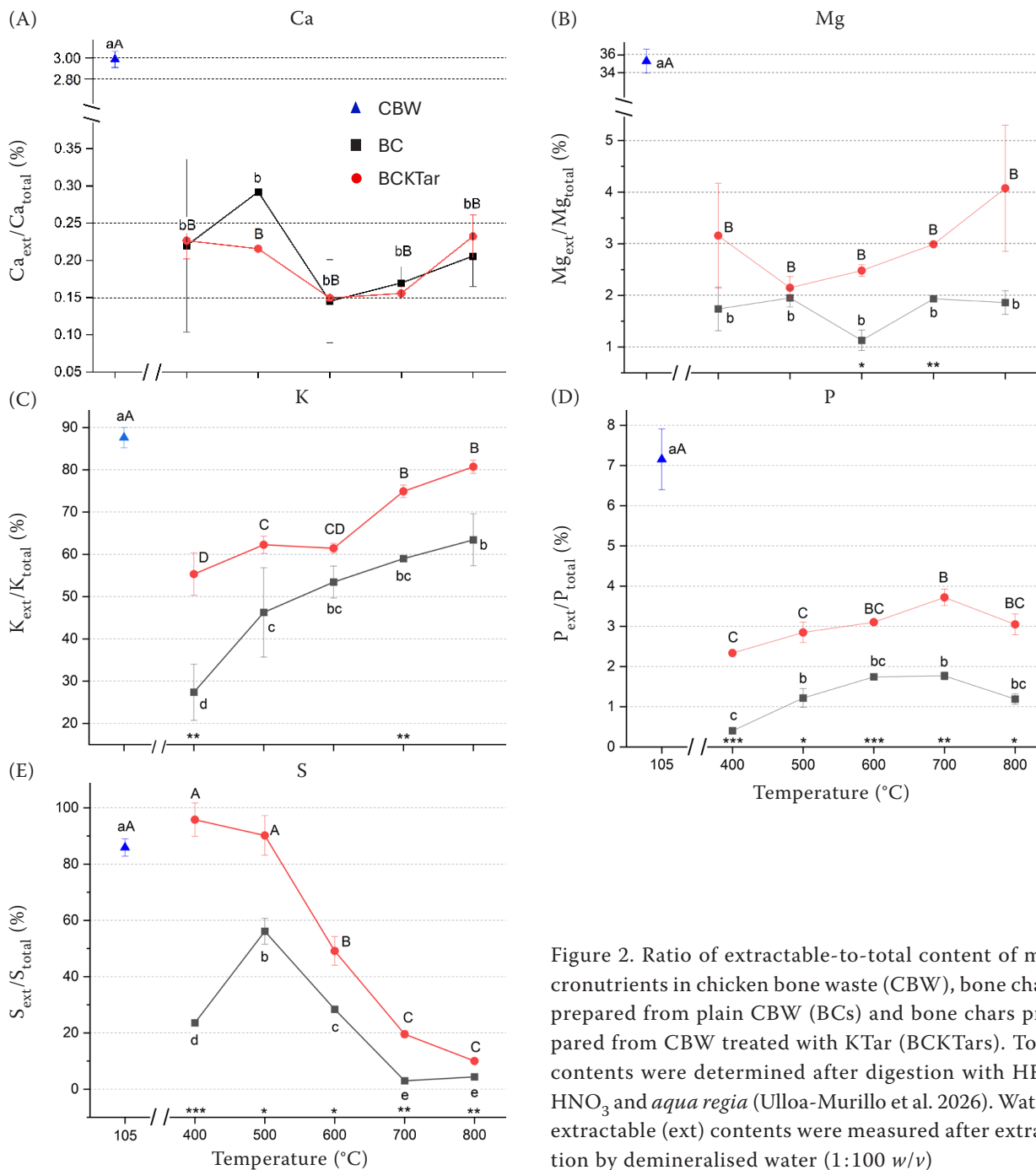


Figure 2. Ratio of extractable-to-total content of macronutrients in chicken bone waste (CBW), bone chars prepared from plain CBW (BCs) and bone chars prepared from CBW treated with KTar (BCKTars). Total contents were determined after digestion with HF + HNO₃ and *aqua regia* (Ulloa-Murillo et al. 2026). Water-extractable (ext) contents were measured after extraction by demineralised water (1:100 w/v)

in BCKTar-400 doubled compared with BC-400 and continued to rise, albeit to a lesser extent, reaching about 81% at 800 °C.

While statistical power is constrained by $n = 2$, the observed differences between the BC and BCKTar treatments are several orders of magnitude larger than their standard deviations, making the statistical significance meaningful.

The $P_{\text{ext}}/P_{\text{total}}$ ratio also increased markedly, by nearly sixfold at 400 °C and by 1.7–2.5 times at higher

temperatures due to the effect of KTar. Buss et al. (2022) similarly reported that low-to-medium pyrolysis temperatures (400–600 °C) are particularly effective in enhancing P availability in K-doped biochars. According to Buss et al. (2020), such effects may result from changes in the extractability of P-binding partners (Ca, Mg, Al, and Fe), which alter P speciation and solubility. Ippolito et al. (2015) also emphasised the controlling role of these cations in P availability. As shown in Figure 2B and Figure 3B,

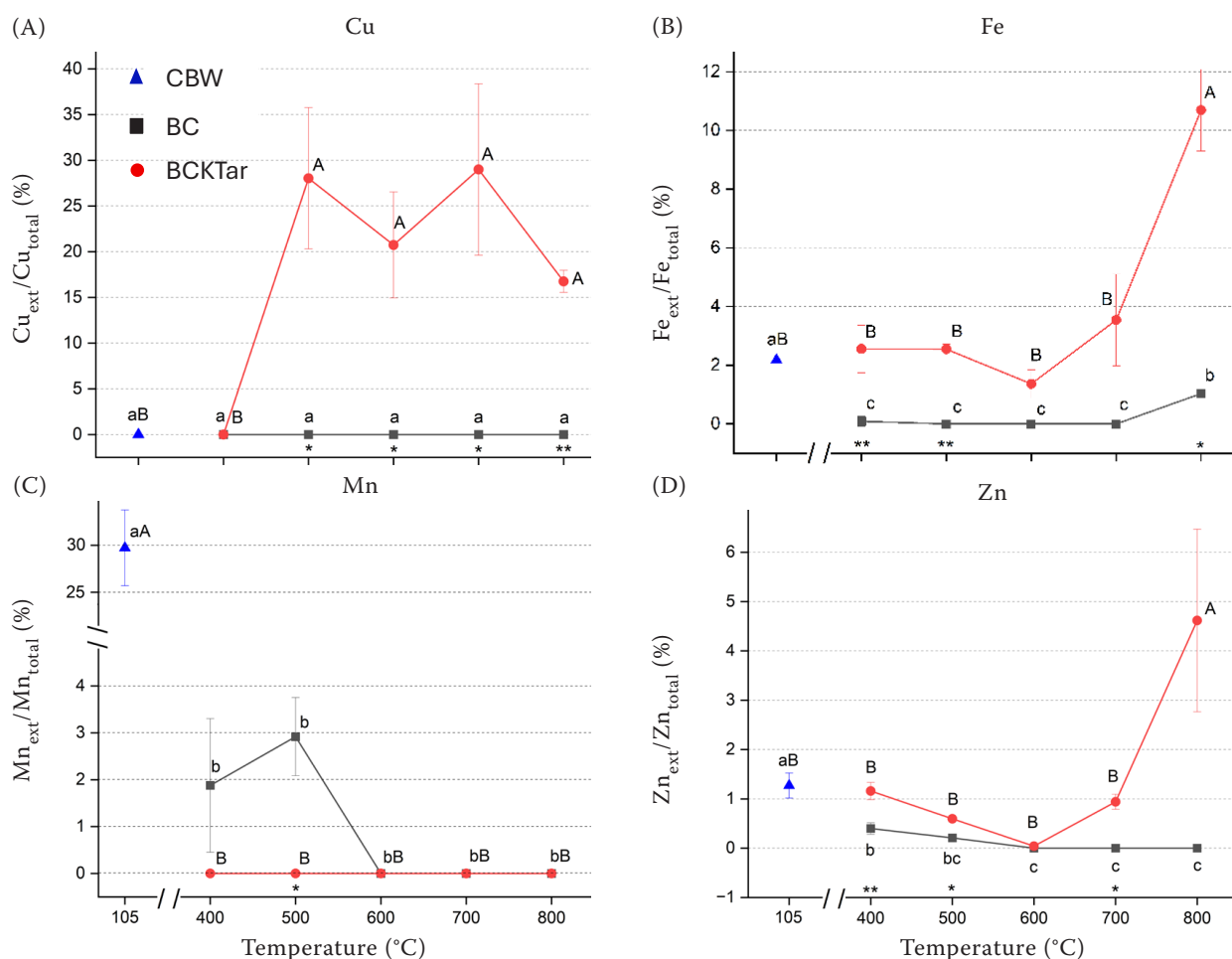


Figure 3. Ratio of extractable-to-total content of micronutrients in chicken bone waste (CBW), bone chars prepared from plain CBW (BCs) and bone chars prepared from CBW treated with KTar (BCKTars). Total contents were determined after digestion with HF + HNO₃ and *aqua regia* (Ulloa-Murillo et al. 2026). Water-extractable (ext) contents were measured after extraction by demineralised water (1:100 w/v)

KTar addition before pyrolysis increased the water-extractable fractions of Mg and Fe in bone chars, implying that the presence of KTar promoted the formation of more soluble Mg and Fe salts during high-temperature treatment.

Regarding other micronutrients, the water-extractable fractions of Cu and Zn increased in BCKTar samples. In contrast, Mn was largely immobilised (Figure 3C). Pyrolysis of the CBW-KTar mixture at ≥ 500 °C produced a pronounced increase (up to 29%) in available Cu. As shown in Figure 4, BCKTar samples are displaced along PC2 relative to BC, consistent with the positive loadings of $\text{Cu}_{\text{ext}}/\text{Cu}_{\text{total}}$ and $\text{Zn}_{\text{ext}}/\text{Zn}_{\text{total}}$, which point toward the BCKTar cluster.

Although the catalytic effects of K salts on elemental availability have been reported by Buss et al. (2020) and Wang et al. (2018), the underlying mechanisms appear to depend strongly on feedstock composition and remain poorly understood. Further investigation

is therefore needed to elucidate the interactions between KTar and CBW during pyrolysis. The PCA (Figure 4) summarises these effects: BCKTar samples occupy an intermediate position between CBW and BC along PC1, reflecting the partial recovery of nutrient extractability, attributed to KTar modification.

Among all treatments, BCKTar-500 obtained during pyrolysis of K-modified feedstock at 500 °C appears to be the most promising for application, as it balances carbon stability with an H/C ratio of 0.83, a bone char yield of 38.3% (Table 1), and high nutrient (P, S, Fe, Cu) water-extractability (Tables 2 and 3).

This study demonstrated that both pyrolysis temperature and potassium tartrate (KTar) addition significantly influence the yield, composition, and nutrient extractability of chicken bone waste-derived chars. The effect of KTar was particularly evident in three key aspects.

First, KTar strongly enhanced sulphur retention. Whereas sulphur was progressively volatilised from

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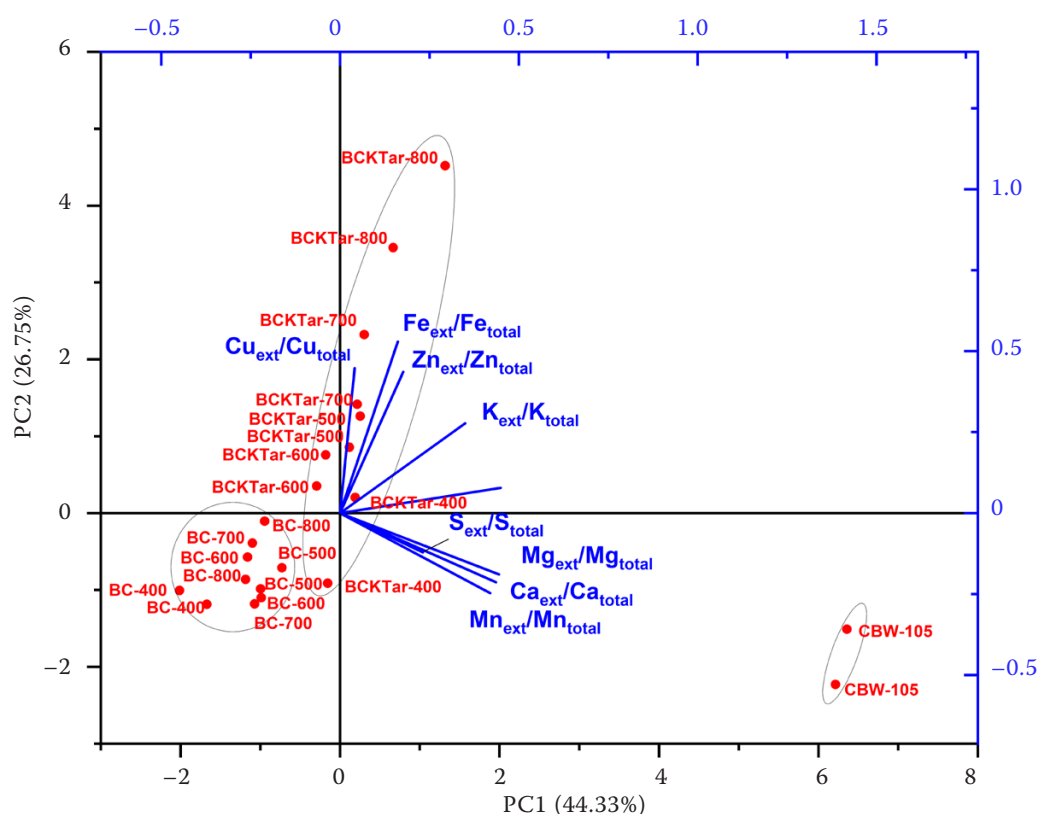


Figure 4. Principal component analysis (PCA) biplot of the first 2 principal components (PC1 and PC2) of extractable to-total nutrient content in chicken bone waste (CBW), bone chars prepared from plain CBW (BC), and bone chars prepared from CBW treated with KTar (BCKTars) pyrolysed at 400–800 °C. Red dots represent sample scores; blue arrows represent variable loadings

unmodified chicken bone waste at temperatures above 400 °C, KTar modification effectively retained sulphur within the solid matrix, resulting in total sulphur contents 55–97% higher than those in unmodified chars. Moreover, at 400 °C, almost all retained sulphur became water-extractable, indicating that KTar can both prevent sulphur losses during pyrolysis and increase its short-term availability.

Second, KTar substantially improved phosphorus availability. The addition of KTar increased both the absolute content of water-extractable phosphorus and its relative solubility. The extractable-to-total phosphorus ratio increased nearly sixfold at 400 °C and remained 1.7–2.5 times higher than that of unmodified bone char at higher pyrolysis temperatures.

Third, KTar markedly altered micronutrient availability and dynamics. The water-extractable contents of iron and copper increased, particularly at temperatures above 500 °C, most likely due to the formation of more soluble mineral salts. Although KTar promoted zinc volatilisation at high temperatures, it also enhanced the extractability of the remaining zinc fraction. In contrast, manganese behaved

differently from the other micronutrients, as it was largely immobilised following KTar modification.

Overall, KTar-assisted pyrolysis represents a promising strategy for improving the agronomic value of bone-derived chars by enhancing the retention and water extractability of selected essential nutrients, especially sulphur and phosphorus. Based on our findings, pyrolysis at 500 °C of KTar-modified feedstock seems to be the optimal treatment for agricultural applications.

To validate the agronomic performance and commercial potential of the obtained bone chars, future research is required, including plant-growth experiments to evaluate nutrient release and crop responses across diverse soil types.

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REFERENCES

- Ahmed M., Nigussie A., Addisu S., Belay B., Sato S. (2021): Valorization of animal bone into phosphorus biofertilizer: effects of animal species, thermal processing method, and production temperature on phosphorus availability. *Soil Science and Plant Nutrition*, 67: 471–481.
- Alkurdi S.S.A., Al-Juboori R.A., Bundschuh J., Bowtell L., McKnight S. (2020): Effect of pyrolysis conditions on bone char characterization and its ability for arsenic and fluoride removal. *Environmental Pollution*, 262: 114221.
- Braidly H., Valin S., Patisson F. (2023): Characterization of sulfur and chlorine behavior during pyrolysis of biomass and waste. *Sustainable Energy and Fuels*, 7: 3067–3076.
- Brod E., Øgaard A.F., Haraldsen T.K., Krogstad T. (2015): Waste products as alternative phosphorus fertilisers part II: predicting P fertilisation effects by chemical extraction. *Nutrient Cycling in Agroecosystems*, 103: 187–199.
- Buss W., Graham M.C., Shepherd J.G., Mašek O. (2016): Risks and benefits of marginal biomass-derived biochars for plant growth. *Science of the Total Environment*, 569–570: 496–506.
- Buss W., Assavavittayanon K., Shepherd J.G., Heal K.V., Sohi S. (2018): Biochar phosphorus release is limited by high pH and excess calcium. *Journal of Environmental Quality*, 47: 1298–1303.
- Buss W., Bogush A., Ignatyev K., Mašek O. (2020): Unlocking the fertilizer potential of waste-derived biochar. *ACS Sustainable Chemistry and Engineering*, 8: 12295–12303.
- Buss W., Wurzer C., Bach M., Heberling J., Appel T., Gerber H., Mašek O. (2022): Highly efficient phosphorus recovery from sludge and manure biochars using potassium acetate pre-treatment. *Journal of Environmental Management*, 314: 115035.
- Cantrell K.B., Hunt P.G., Uchimiya M., Novak J.M., Ro K.S. (2012): Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresource Technology*, 107: 419–428.
- Cascarosa E., Fonts I., Mesa J.M., Sánchez J.L., Arauzo J. (2011): Characterization of the liquid and solid products obtained from the oxidative pyrolysis of meat and bone meal in a pilot-scale fluidised bed plant. *Fuel Processing Technology*, 92: 1954–1962.
- Chen W., Gong M., Li K., Xia M., Chen Z., Xiao H., Fang Y., Chen Y., Yang H., Chen H. (2020a): Insight into KOH activation mechanism during biomass pyrolysis: chemical reactions between O-containing groups and KOH. *Applied Energy*, 278: 115730.
- Chen Z., Yu G., Wang Y., Wang X. (2020b): Fate of heavy metals during co-disposal of municipal solid waste incineration fly ash and sewage sludge by hydrothermal coupling pyrolysis process. *Waste Management*, 109: 28–37.
- Choi H., Won C.S., Kim B.G. (2021): Protein and energy concentrations of meat meal and meat and bone meal fed to pigs based on *in vitro* assays. *Animal Nutrition*, 7: 252–257.
- Dela Piccola C., Hesterberg D., Muraoka T., Novotny E.H. (2021): Optimising pyrolysis conditions for recycling pig bones into phosphate fertiliser. *Waste Management*, 131: 249–257.
- Fan H., Gu J., Wang Y., Yuan H., Chen Y., Luo B. (2021): Effect of potassium on the pyrolysis of biomass components: pyrolysis behaviors, product distribution and kinetic characteristics. *Waste Management*, 121: 255–264.
- Feng Y., Wan L., Wang S., Yu T., Chen D. (2018): The emission of gaseous nitrogen compounds during pyrolysis of meat and bone meal. *Journal of Analytical and Applied Pyrolysis*, 130: 314–319.
- Frišták V., Pipiška M., Koperová D., Jägerhofer R., Soja G., Bell S.M. (2022): Utilisation of sewage sludge-derived pyrogenic material as a promising soil amendment. *Agriculture*, 12: 360.
- Frišták V., Pipiška M., Soja G. (2019): Agro-environmental benefit and risk of manure- and bone meal-derived pyrogenic carbonaceous materials as soil amendments: availability of PAHs, PTEs, and P. *Agronomy*, 9: 802.
- Gunes A., Inal A., Sahin O., Taskin M.B., Atakol O., Yilmaz N. (2015): Variations in mineral element concentrations of poultry manure biochar obtained at different pyrolysis temperatures, and their effects on crop growth and mineral nutrition. *Soil Use and Management*, 31: 429–437.
- Guo S., Wang Y., Yang L., Sun B., Qu H., Li X., Zhao D. (2024): ReaxFF-based molecular dynamics simulation of the impact of potassium on the formation of NH₃ during protein pyrolysis. *Energy*, 313: 134059.
- Hart A., Ebiundu K., Peretomode E., Onyeaka H., Nwabor O., Obileke K. (2022): Value-added materials recovered from waste bone biomass: technologies and applications. *RSC Advances*, 12: 22302–22330.
- He Y.D., Zhai Y.B., Li C.T., Yang F., Chen L., Fan X.P., Peng W.F., Fu Z.M. (2010): The fate of Cu, Zn, Pb and Cd during the pyrolysis of sewage sludge at different temperatures. *Environmental Technology*, 31: 567–574.
- Hossain M.K., Strezov V., Chan K.Y., Ziolkowski A., Nelson P.F. (2011): Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *Journal of Environmental Management*, 92: 223–228.
- Ippolito J.A., Spokas K.A., Novak J.M., Lehmann J., Joseph S. (2015): Biochar elemental composition and factors influencing nutrient retention. In: Lehmann J., Joseph S. (eds.): *Biochar for Environmental Management: Science, Technology and Implementation*. Routledge, Routledge, 139. ISBN: 978-1-032-28615-0
- Kantorek M., Jesionek K., Polesek-Karczewska S., Ziolkowski P., Badur J. (2019): Thermal utilization of meat and bone meals: performance analysis in terms of drying process, pyrolysis and kinetics of volatiles combustion. *Fuel*, 254: 115548.
- Kratz S., Haneklaus S., Schnug E. (2010): Chemical solubility and agricultural performance of P-containing recycling fertilisers. *Landbauforschung Volkenrode*, 60: 227–240.

<https://doi.org/10.17221/323/2026-PSE>

- Leinweber P., Hagemann P., Kebelmann L., Kebelmann K., Morshedizad M. (2019): Bone char as a novel phosphorus fertiliser. In: Ohtake H., Tsuneda S. (eds.): Phosphorus Recovery and Recycling. Singapore, Springer, 419–432. ISBN: 978-981-10-8030-2
- Lin B., Mallah M.M.A.M., Huang Q., Ali M., Chi Y. (2017): Effects of temperature and potassium compounds on the transformation behavior of sulfur during pyrolysis of oily sludge. *Energy and Fuels*, 31: 7004–7014.
- Mašek O., Buss W., Brownsort P., Rovere M., Tagliaferro A., Zhao L., Cao X., Xu G. (2019): Potassium doping increases biochar carbon sequestration potential by 45%, facilitating decoupling of carbon sequestration from soil improvement. *Scientific Reports*, 9: 5514.
- Mercl F., Košnář Z., Pierdonà L., Ulloa-Murillo L.M., Száková J., Tlustoš P. (2020): Changes in availability of Ca, K, Mg, P and S in sewage sludge as affected by pyrolysis temperature. *Plant, Soil and Environment*, 66: 143–148.
- Park J.H., Wang J.J., Kim S.H., Kang S.W., Cho J.S., Delaune R.D., Ok Y.S., Seo D.C. (2019): Lead sorption characteristics of various chicken bone part-derived chars. *Environmental Geochemistry and Health*, 41: 1675–1685.
- Sugawara K., Abe K., Sugawara T., Nishiyama Y., Sholest M.A. (1995): Dynamic behaviour of sulfur forms in rapid pyrolysis of coals with alkali treatment. *Fuel*, 74: 1823–1829.
- Taisheva A., Doležal P., Ulloa-Murillo L.M., Tejnecký V., Száková J., Tlustoš P., Mercl F. (2026): *In-situ* potassium hydroxide catalysis improves bio-oil composition and bone-char quality during pyrolysis of chicken meat-bone waste. *Waste Management*, 211: 115299.
- Tu W., Liu Y., Xie Z., Chen M., Ma L., Du G., Zhu M. (2021): A novel activation-hydrochar via hydrothermal carbonisation and KOH activation of sewage sludge and coconut shell: preparation, characterization and adsorption properties. *Journal of Colloid and Interface Science*, 593: 390–407.
- Ulloa-Murillo L.M., Kučera J., Tejnecký V., Taisheva A., Paul C.S., Košnář Z., Száková J., Tlustoš P., Mercl F. (2026): Optimization of digestion methods for total elemental analysis in sewage sludge biochars. *Chemical and Biological Technologies in Agriculture*. <https://doi.org/10.1186/s40538-026-00974-4>
- Wang M., Wang J.J., Wang X. (2018): Effect of KOH-enhanced biochar on increasing soil plant-available silicon. *Geoderma*, 321: 22–31.
- Xia Y., Tang Y., Shih K., Li B. (2020): Enhanced phosphorus availability and heavy metal removal by chlorination during sewage sludge pyrolysis. *Journal of Hazardous Materials*, 382: 121110.
- Xu G., Zhang Y., Shao H., Sun J. (2016): Pyrolysis temperature affects phosphorus transformation in biochar: chemical fractionation and ³¹P NMR analysis. *Science of the Total Environment*, 569–570: 65–72.
- Xu Q., Chen Y., Feng Y., Xian S., Wu Y., Li H., Zhang Z., Chen B. (2026): Decoupling the influence of terrestrial biomass on microwave pyrolysis of seaweed and sulfur migration. *Industrial Crops and Products*, 239: 122503.
- Zhang H., Tao W., Hou M., Ran M., Chen C., Liu J., Tu L., Huang L., Deng P., Chen D., Wu Y. (2023): Effect of potassium ferrate as a dewatering conditioner on sludge pyrolysis characteristics and the releasing characteristics of nitrogen, sulfur, and chlorine during sewage sludge pyrolysis. *Processes*, 11: 920.
- Zielińska A., Oleszczuk P. (2015): The conversion of sewage sludge into biochar reduces polycyclic aromatic hydrocarbon content and ecotoxicity but increases trace metal content. *Biomass and Bioenergy*, 75: 235–244.
- Zwetsloot M.J., Lehmann J., Solomon D. (2015): Recycling slaughterhouse waste into fertiliser: how do pyrolysis temperature and biomass additions affect phosphorus availability and chemistry? *Journal of the Science of Food and Agriculture*, 95: 281–288.

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