

Fishbone Biochar as a Circular Phosphorus Source in Dryland Soils

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Abstract

Phosphorus scarcity and poor phosphorus availability remain major constraints in alkaline dryland soils, where fertilizer P efficiency is commonly limited by calcium-phosphate precipitation and strong soil buffering. At the same time, fishbone residues are often discarded despite their high mineral phosphorus value. This study evaluated fishbone biochar (FBBC) as a locally produced circular phosphorus source rich in Olsen-extractable P in three contrasting Sudanese dryland soil materials representing Vertisol, Entisol and Aridisol conditions. A 112-day controlled incubation experiment was arranged as a $3 \times 3 \times 7$ factorial design, including three soils, three FBBC rates (0, 2.5 and 5% w/w), seven incubation periods (1, 3, 7, 14, 28, 56 and 112 days) and three replicates, giving 189 experimental units. Replicate-level data were analysed using fixed-effect factorial ANOVA, effect-size estimates, soil-specific contrasts and Pearson correlation analysis. The FBBC was alkaline (pH 9.1), moderately saline (EC 2.18 dS m⁻¹), calcium-rich (Ca²⁺ 3.5 meq L⁻¹), low in sodium hazard (SAR 1.1) and highly enriched in Olsen-extractable P (4999 mg kg⁻¹). Available P was significantly controlled by soil type, FBBC rate, incubation time and their three-way interaction ($p < 0.001$), showing that the response was governed by both amendment dose and soil-specific buffering behaviour. Across the incubation period, 5% FBBC increased mean available P by 108.0% in Vertisol, 60.4% in Entisol and 138.7% in Aridisol, while 2.5% FBBC produced gains of 72.9, 31.4 and 116.3%, respectively. Although the estimated Olsen-P inputs were approximately 125 and 250 mg P kg⁻¹ soil at the 2.5 and 5% rates, respectively, the recovered soil Olsen-P was much lower, indicating strong retention, sorption and calcium-phosphate re-equilibration within the receiving soils. EC changes were modest in Vertisol and Entisol, but the 5% rate increased EC in Aridisol. SAR was governed mainly by soil type and reached its highest values in Vertisol. These results support fishbone biochar as a concentrated circular phosphorus source for dryland soils, provided that application rates are guided by soil-specific screening of P availability, salinity and sodicity. Conservative initial rates, particularly 2.5%, should be validated first, with attention to possible P mobility in sandy soils and sodicity risk in Vertisols.

1. Introduction

Phosphorus management in dryland agriculture sits at the intersection of resource scarcity and low fertilizer efficiency. Phosphate rock is a finite resource, while many arid and semi-arid soils convert added phosphorus into forms that plants cannot easily access. In alkaline and calcareous soils, soluble phosphate can rapidly react with calcium and carbonate-rich soil constituents, forming sparingly soluble calcium-phosphate phases. As a result, only a fraction of applied P remains available to plants, while farmers continue to depend on repeated fertilizer inputs. This problem is particularly important where fertilizer costs are high and where production systems have limited capacity to absorb further increases in input prices (Richards, 1954; Olsen et al., 1954; Lindsay, 1979; Barrow, 1983; Marschner, 1995; Whitelaw, 1999; Raghothama, 1999; Stevenson & Cole, 1999; Frossard et al., 2000; Hinsinger, 2001; Sparks, 2003; Vance et al., 2003; Syers et al., 2008; Brady & Weil, 2016; FAO, 2021).

Circular nutrient recovery offers a practical pathway to reduce this dependence on external mineral fertilizers. Fishbone residues are especially relevant in Nile-based food systems because they contain

calcium-phosphate minerals that can be recovered and redirected into phosphorus recycling in dryland soils. When fish bones are thermally treated under low-oxygen conditions, the resulting char differs fundamentally from plant-derived biochars. Conventional plant biochars are commonly valued for their carbon stability, porous structure, sorption capacity and effects on soil physical condition. Fishbone biochar, by contrast, should be viewed primarily as a calcium-phosphorus amendment with an additional carbonaceous fraction, rather than as a purely carbon-based soil conditioner (Glaser et al., 2002; Cheng et al., 2006; Chan et al., 2007; Steiner et al., 2007; Warnock et al., 2007; Lehmann & Joseph, 2009; Novak et al., 2009; Atkinson et al., 2010; Kwapinski et al., 2010; Laird et al., 2010; Major et al., 2010; Singh et al., 2010; Sohi et al., 2010; Van Zwieten et al., 2010; Woolf et al., 2010; Zhang et al., 2010).

This distinction matters because the performance of any biochar depends strongly on its feedstock, thermal history, ash content, pH, electrical conductivity, soluble ions and nutrient-release behaviour. It also depends on the receiving soil. A biochar that improves nutrient availability in one soil may increase salinity, sodicity or nutrient mobility in another. These controls become especially important when biochar is used as a nutrient-recovery material rather than only as a carbon amendment. The wider biochar literature has shown that amendment behaviour is shaped by interactions among biochar chemistry, soil texture, pH, mineral surfaces, microbial activity, water retention and salt dynamics (Brewer et al., 2011; Jeffery et al., 2011; Karhu et al., 2011; Kookana et al., 2011; Beesley et al., 2011; Cantrell et al., 2012; Enders et al., 2012; Spokas et al., 2012; Taghizadeh-Toosi et al., 2012; Yao et al., 2012; Biederman & Harpole, 2013; Mukherjee & Zimmerman, 2013; Qian et al., 2013; Al-Wabel et al., 2013; Parvage et al., 2013; Bolan et al., 2014; DeLuca et al., 2015; Gul et al., 2015; Kizito et al., 2015; Ding et al., 2016; Gao et al., 2016; Agegnehu et al., 2017; Blanco-Canqui, 2017; Li et al., 2019; Ippolito et al., 2020; Razzaghi et al., 2020). For example, Gao et al. (2016) showed that locally produced wood biochar can increase nutrient retention and availability in agricultural soils, highlighting the importance of assessing biochar performance in relation to both feedstock properties and receiving-soil conditions.

Fishbone biochar therefore cannot be interpreted through the same lens used for wood- or crop-residue biochars. Bone char is expected to contain hydroxyapatite-like mineral phases, together with calcium, magnesium and phosphorus-bearing compounds. Its release of P is likely governed by mineral dissolution, soil pH, calcium activity, carbonate chemistry, sorption capacity and biological acidification, rather than by decomposition of a purely organic nutrient pool. Previous work on fish-bone hydroxyapatite, animal bone char and recycled phosphorus materials supports this interpretation. These materials can increase Olsen-P in soil, but their release behaviour is often gradual, soil-dependent and controlled by time-dependent dissolution and re-equilibration processes. In dryland soils, this behaviour requires direct testing because high pH, carbonate buffering, low rainfall and restricted leaching can alter both P availability and salt accumulation (Ozawa & Kanahara, 2005; Prijambada et al., 2009; Warren et al., 2009; Siebers & Leinweber, 2013; Siebers et al., 2014; Zwetsloot et al., 2016; Zheng et al., 2019; Schütze et al., 2020; Amin, 2024).

The potential benefit of fishbone biochar must also be weighed against chemical risk. Ash-rich amendments can raise soil pH and electrical conductivity, while materials containing appreciable soluble

sodium may increase sodicity hazard. Even where the amendment itself has low SAR, the final soil response may still depend on baseline soil chemistry and texture. This is critical in dryland environments, where high evaporation and limited natural leaching can allow salts to accumulate over time. Sodium-related risk is particularly important in clay-rich soils because elevated SAR can promote clay dispersion, reduce permeability and impair soil structure. For this reason, fishbone biochar should be assessed as a nutrient–risk material, in which available P, pH, EC and SAR are interpreted together rather than separately (Quirk & Schofield, 1955; Frenkel et al., 1978; Shainberg & Letey, 1984; Rengasamy, 2010; Kameyama et al., 2012; Chaganti & Crohn, 2015; Rengasamy, 2016).

Despite increasing interest in biochar and recycled nutrient sources, evidence remains limited on how locally produced fishbone biochar behaves in contrasting dryland soils under controlled incubation. The main issue is not whether fishbone biochar contains phosphorus, since its calcium-phosphate composition already confirms that. The more important question is whether an Olsen-P-rich fishbone biochar can increase soil available P without creating undesirable salinity, sodicity, or P-mobility signals. This question is important for Sudanese dryland soils, where Vertisol, Entisol, and Aridisol materials differ markedly in texture, mineral buffering, exchange behaviour, baseline salinity, and nutrient-retention capacity (Klute, 1986; Soil Survey Staff, 2022; IUSS Working Group WRB, 2022).

The objective of this study was to evaluate fishbone biochar as a circular phosphorus source applied at 2.5% and 5% w/w to Vertisol, Entisol, and Aridisol materials during a 112-day incubation, with emphasis on available P, pH, EC, and SAR responses. The study tested three hypotheses: first, FBBC would increase soil available P, but the response would vary with soil type, application rate, and incubation time; second, the 5% rate would not necessarily produce a proportional improvement over 2.5% because soil buffering, calcium-phosphate reactions, and sorption processes would regulate P recovery; and third, the low intrinsic SAR of FBBC would limit direct sodium addition, although the final SAR response would remain controlled by the receiving soil.

2. Materials and methods

2.1 Experimental site and soil materials

The incubation experiment was conducted at the Soil and Water Laboratory, College of Agricultural Studies, Sudan University of Science and Technology, Shambat, Sudan. Three soil materials were selected to represent contrasting Sudanese dryland and alluvial soil conditions: a clay-rich Vertisol, an Entisol and a sandy Aridisol. According to the original laboratory record, these materials were collected from Al-Qadarif State, Al-Jarif, and West Omdurman, respectively. They were selected because they differ clearly in texture, salinity status, sodium hazard, carbonate chemistry and phosphorus-retention capacity, providing a suitable basis for comparing the response to fishbone biochar across distinct soil matrices.

The collected materials were treated as representative laboratory soil materials rather than as fully replicated field profiles. This approach was appropriate because the objective of the incubation

experiment was to compare contrasting soil matrices under controlled laboratory conditions, not to quantify field-scale spatial variability within each soil type.

After collection, the soil materials were air-dried under laboratory conditions, gently crushed and passed through a 2-mm sieve before incubation. The sieved materials were homogenized before amendment application to reduce within-sample variability. Baseline physicochemical properties, including pH, ECe, soluble ions, SAR, Olsen-P, CaCO₃, particle-size distribution, texture class, bulk density and particle density, were determined before incubation and are presented in Table 1. These initial properties provided the reference condition against which the effects of FBBC addition were evaluated.

Table 1
Initial physicochemical properties of the three soil materials used in the incubation experiment.

Soil property	Unit	Vertisol	Entisol	Aridisol
pH	—	7.60	7.60	7.70
ECe	dS m ⁻¹	6.00	1.27	5.00
CO ₃ ²⁻	meq L ⁻¹	3.50	5.00	0.00
HCO ₃ ⁻	meq L ⁻¹	6.00	7.00	3.30
Cl ⁻	meq L ⁻¹	2.00	2.00	1.00
Soluble Na ⁺	meq L ⁻¹	21.80	2.00	6.00
Ca ²⁺ + Mg ²⁺	meq L ⁻¹	8.00	3.00	5.00
K ⁺	meq L ⁻¹	0.17	0.26	1.00
SAR	—	10.90	1.60	1.30
Olsen-P	mg kg ⁻¹	0.50	2.60	0.36
CaCO ₃	%	3.50	3.50	2.30
Clay	%	60.00	52.00	10.00
Sand	%	20.00	22.00	70.00
Silt	%	30.00	24.00	20.00
Texture class	—	Clay	Clay loam	Sand
Bulk density	g cm ⁻³	1.60	1.55	1.40
Particle density	g cm ⁻³	2.80	2.50	2.10

Note. ECe = electrical conductivity of the saturated paste extract; SAR = sodium adsorption ratio; Olsen-P = sodium bicarbonate-extractable phosphorus. Baseline ECe values are reported for initial soil characterization only, whereas incubation EC responses were measured in 1:5 soil–water extracts. Particle density is used here instead of real density to align with standard soil science terminology.

The three soil materials showed clear contrasts in texture, salinity, sodicity and initial phosphorus availability. The Vertisol was clay-rich, saline and characterized by the highest soluble Na^+ and SAR values, indicating strong buffering capacity but also greater sodium-related structural risk. The Entisol had lower salinity and sodicity, with the highest initial Olsen-P among the three soils. The Aridisol was sandy, low in available P and weakly buffered, suggesting a higher probability of rapid response to FBBC addition but also a greater need to assess soluble salt response and potential P mobility. These baseline differences justified treating soil type as a primary factor in the incubation experiment rather than as a background condition.

2.2 Fishbone biochar preparation and screening

Fishbone residues were collected from Al-Mourada market, Omdurman. The preparation sequence is illustrated in Fig. 1. Briefly, the residues were washed, cleaned of adhering organic matter and air-dried before thermal treatment. The dried fishbone material was placed in a small inner metal container, sealed with clay to restrict oxygen entry, and then loaded into a larger drum kiln. The material was thermally treated for approximately two hours under traditional low-oxygen conditions. After cooling, the charred product was recovered, crushed and sieved before use. Because the pyrolysis temperature was not monitored, the material is interpreted as locally produced fishbone biochar rather than as a standardized industrial biochar.

The FBBC screening analysis included pH, EC, soluble cations, SAR and Olsen-extractable P. Notably, the FBBC exhibited an exceptionally high concentration of Olsen-extractable phosphorus (4999 mg kg^{-1}), highlighting its potential as a highly concentrated direct P source rather than a conventional carbonaceous soil conditioner. Its measured chemical properties and expected soil implications are presented in Table 2.

Table 2
Chemical properties of fishbone biochar and expected soil implications.

Property	Unit	Observed value	Interpretation	Expected soil implication
pH	-	9.10	Alkaline	May buffer or increase soil pH depending on soil buffering capacity
EC	dS m ⁻¹	2.18	Moderate soluble salt signal	Requires EC screening at high application rates
Ca ²⁺ + Mg ²⁺	meq L ⁻¹	4.30	High divalent-cation contribution	Supports calcium-phosphate chemistry and may reduce sodium dominance
Ca ²⁺	meq L ⁻¹	3.50	Calcium-rich	Important for Ca-P reactions and exchange chemistry
Soluble Na ⁺	meq L ⁻¹	1.60	Low sodium input	Low direct sodicity burden
SAR	-	1.10	Low sodium hazard	Lower sodium risk than sodium-rich biochars
Soluble K ⁺	meq L ⁻¹	0.67	Low K contribution	Minor soluble K input
Olsen-extractable P	mg kg ⁻¹	4999	Exceptionally high extractable P pool	Provides a large direct Olsen-P input; soil retention and Ca-P reactions control recovered soil Olsen-P

2.3 Incubation design

The incubation experiment was arranged as a 3 × 3 × 7 factorial design under a completely randomized layout. The experimental factors were soil type, FBBC application rate and incubation time. The three soil materials represented contrasting dryland soil conditions: Vertisol, Entisol and Aridisol. The amendment treatments consisted of an unamended control, 2.5% FBBC and 5% FBBC on a dry-weight basis. Each incubation unit contained 200 g of air-dried soil. For the amended treatments, FBBC was thoroughly mixed with the soil at the assigned rate before incubation.

The incubation periods were 1, 3, 7, 14, 28, 56 and 112 days. Each soil–rate–time combination was prepared in three replicates. This resulted in nine soil–rate treatment combinations at each sampling time and a total of 189 experimental units across the full incubation period. At each sampling date, the corresponding pots were destructively sampled and analysed for available P, pH, EC, soluble Na⁺, Ca²⁺ + Mg²⁺ and SAR. The full treatment structure is summarized in Table 3.

Table 3
Incubation experimental design and treatment structure

Experimental factor	Levels	Description
Soil type	Vertisol, Entisol, Aridisol	Three contrasting soil materials
FBBC rate	0, 2.5, 5% w/w	Control and two amendment rates
Incubation time	1, 3, 7, 14, 28, 56, 112 days	Destructive sampling dates
Replication	3	Three replicates per soil × rate × time
Total units	189	$3 \times 3 \times 7 \times 3$

2.4 Moisture management and destructive sampling

Pots were incubated under laboratory temperatures of approximately 30–35°C. Soil moisture was maintained close to an operational field-capacity condition by weighing the pots every two days and adding water gravimetrically to compensate for mass loss. This approach was used to keep the incubation conditions comparable among soils, FBBC rates and sampling dates.

The experiment followed a destructive sampling procedure. At each scheduled incubation time (1, 3, 7, 14, 28, 56 and 112 days), the corresponding pots were harvested completely and removed from the experiment. The same pots were not sampled repeatedly or returned to continue incubation. The harvested soil from each pot was then processed for the determination of pH, EC, available P, soluble Na⁺, Ca²⁺ + Mg²⁺ and SAR.

This design was intended to isolate soil-process responses under controlled and comparable moisture and temperature conditions, rather than to simulate full field dynamics. It also avoided disturbance effects that could arise from repeated subsampling of the same pot during incubation.

2.5 Laboratory analyses

Soil pH and EC during incubation were measured in 1:5 (w/v) soil–water extracts using standard laboratory procedures. Baseline salinity in Table 1 was reported as E_{Ce} from saturated paste extract, whereas incubation EC responses were measured in 1:5 soil–water extracts. Therefore, EC values from baseline characterization and incubation monitoring were interpreted separately. Available P was determined using 0.5 M NaHCO₃ extraction at pH 8.5, following the Olsen method and quantified colorimetrically. Soluble Na⁺ was measured by flame photometry, while Ca²⁺ and Mg²⁺ were determined by EDTA titration. SAR was calculated from soluble Na⁺, Ca²⁺ and Mg²⁺ concentrations using the standard irrigation-water expression, with concentrations expressed in meq L⁻¹. Particle-size distribution and related soil characterization followed standard soil physical and chemical methods where applicable (Richards, 1954; Bouyoucos, 1962; Chapman, 1965; Klute, 1986; Olsen & Sommers, 1982; McLean, 1982; Tan, 2010).

2.6 Statistical analysis

Replicate-level data for available P, pH, EC and SAR were checked for completeness, consistency and treatment coding, then reorganized into long format. The experiment was analysed as a fixed-effect $3 \times 3 \times 7$ factorial design, with soil type, FBBC rate and incubation time as fixed factors. Soil type included Vertisol, Entisol and Aridisol; FBBC rate included 0, 2.5 and 5% w/w; and incubation time included 1, 3, 7, 14, 28, 56 and 112 days. The full design comprised 189 experimental units.

Data checks confirmed 189 observations for available P, pH and EC. SAR had one missing replicate value in the Aridisol control at day 28; therefore, SAR-based analyses and the integrated correlation matrix used the available replicate-level records without imputation. Available P, pH and SAR were analysed using factorial ANOVA with all main effects, two-way interactions and the three-way interaction included in the model:

$$Y = \text{Soil} + \text{Rate} + \text{Time} + \text{Soil} \times \text{Rate} + \text{Soil} \times \text{Time} + \text{Rate} \times \text{Time} + \text{Soil} \times \text{Rate} \times \text{Time} + \text{error}$$

EC was log-transformed before ANOVA because the raw values were positive and right-skewed. Statistical significance was assessed at $p < 0.05$, and effect magnitude was reported as partial eta squared. Soil-specific treatment effects were calculated relative to the corresponding unamended control, and percentage changes were used to describe treatment direction and practical magnitude. Time-specific summaries were used to identify peak available P values and day-112 responses.

Pearson correlation coefficients and two-tailed p-values were calculated using replicate-matched values of available P, pH, EC and SAR. The correlation matrix was used as an exploratory tool to describe co-variation among nutrient, salinity and sodicity indicators, not as evidence of direct causality. Model outputs were interpreted together with treatment means, standard deviations, percentage changes and graphical summaries, with emphasis on the balance between P gain, EC response and SAR risk.

All statistical analyses were performed in R version 4.6.0. Model residuals were inspected using residual-fitted plots and normal Q-Q plots, and homogeneity of variance was assessed through residual diagnostics.

3. Results

The results are presented within the conceptual sequence shown in Fig. 2, which links fishbone residues to the production of Olsen-P-rich FBBC and its subsequent evaluation in contrasting dryland soil matrices. The results are organized to show the amendment properties, the baseline soil context and the treatment effects on available P, pH, EC and SAR. Accordingly, the results first describe the amendment and baseline soil context, then evaluate the factorial effects of soil type, FBBC rate and incubation time on available P, pH, EC and SAR.

3.1 Fishbone biochar and baseline soil chemistry defined the nutrient–risk context

The chemical screening of FBBC showed that the material was not a neutral carbon amendment. It combined an alkaline reaction, moderate soluble salt content, a calcium-rich ionic profile, low sodium hazard and an exceptionally large Olsen-extractable P pool (Table 2). The corrected Olsen-P concentration of 4999 mg kg⁻¹ is therefore central to the interpretation of the experiment. This concentration identifies FBBC as a calcium-bearing P amendment with a large extractable P pool, rather than a low-nutrient soil conditioner.

At the 2.5 and 5% application rates, the estimated Olsen-P inputs were approximately 125 and 250 mg P kg⁻¹ soil, respectively. These theoretical inputs were far greater than the increases recovered as soil Olsen-P during incubation. This difference shows that the receiving soils did not behave as passive carriers of the added P. Instead, a large fraction of the added extractable P was likely buffered, retained, transformed or re-equilibrated through soil-specific reactions involving clay surfaces, carbonate chemistry, calcium activity and phosphate sorption.

The initial soil properties also differed markedly (Table 1), providing a clear basis for treating soil type as a primary experimental factor. The Vertisol had the highest clay content, ECe and SAR, indicating strong buffering capacity but also greater sensitivity to sodium-related structural risk. The Entisol showed lower salinity and sodicity, suggesting a more moderate chemical constraint. The Aridisol, by contrast, was sandy and had low initial available P, indicating weaker buffering and a greater likelihood of rapid response to FBBC addition. These contrasts framed the experiment as a soil-specific nutrient–risk assessment rather than a simple amendment-rate comparison.

3.2 Factorial ANOVA showed strong soil–rate–time control of the response

The factorial ANOVA confirmed that the chemical response of the incubation system was controlled by the combined effects of soil type, FBBC rate and incubation time (Table 4). Available P showed a strong factorial structure, with significant main effects and all two-way and three-way interactions. The strongest effect was associated with FBBC rate, followed by incubation time and soil type, confirming that the Olsen-P-rich amendment produced a rate-dependent response that was strongly moderated by the receiving soil and the duration of incubation.

pH, log-transformed EC and SAR also showed significant factorial responses, but the dominant source of variation differed among variables. Soil type explained the largest share of variation in pH, log EC and SAR, indicating that baseline soil chemistry, texture and buffering capacity strongly shaped the chemical risk profile. The three-way interaction was significant for available P, log EC and SAR, but not for pH, showing that pH response was less dependent on the combined soil–rate–time structure than the nutrient, salinity and sodicity indicators.

Table 4
Factorial ANOVA summary for chemical responses based on replicate-level data.

Response	Source	df	F-value	p-value	Partial eta²
Available P	Soil type	2	258.319	< 0.001	0.804
	FBBC rate	2	576.321	< 0.001	0.901
	Incubation time	6	167.304	< 0.001	0.888
	Soil × Rate	4	25.111	< 0.001	0.444
	Soil × Time	12	83.081	< 0.001	0.888
	Rate × Time	12	22.404	< 0.001	0.681
	Soil × Rate × Time	24	45.666	< 0.001	0.897
pH	Soil type	2	492.165	< 0.001	0.887
	FBBC rate	2	18.001	< 0.001	0.222
	Incubation time	6	16.368	< 0.001	0.438
	Soil × Rate	4	13.067	< 0.001	0.293
	Soil × Time	12	5.582	< 0.001	0.347
	Rate × Time	12	2.946	0.0012	0.219
	Soil × Rate × Time	24	1.397	0.1214	0.210
log EC	Soil type	2	878.942	< 0.001	0.933
	FBBC rate	2	5.152	0.0071	0.076
	Incubation time	6	17.589	< 0.001	0.456
	Soil × Rate	4	10.352	< 0.001	0.247
	Soil × Time	12	3.723	< 0.001	0.262
	Rate × Time	12	1.866	0.0447	0.151
	Soil × Rate × Time	24	1.934	0.0104	0.269
SAR	Soil type	2	1805.605	< 0.001	0.966
	FBBC rate	2	95.989	< 0.001	0.604
	Incubation time	6	20.789	< 0.001	0.497
	Soil × Rate	4	25.995	< 0.001	0.452
	Soil × Time	12	13.139	< 0.001	0.556

Response	Source	df	F-value	p-value	Partial eta ²
	Rate × Time	12	4.733	< 0.001	0.311
	Soil × Rate × Time	24	5.506	< 0.001	0.512

3.3 Available phosphorus increased in a soil- and rate-specific manner

FBBC increased available P in all soil materials, but the magnitude and timing of the response differed (Fig. 3; Tables 5 and 6). Across the full incubation, 5% FBBC increased mean available P by 108.0% in Vertisol, 60.4% in Entisol and 138.7% in Aridisol. The 2.5% rate also produced clear gains, increasing available P by 72.9, 31.4 and 116.3% in Vertisol, Entisol and Aridisol, respectively.

Peak P values further illustrate the interaction. Vertisol reached its highest mean available P at day 56 under 5% FBBC (20.23 mg kg⁻¹). Aridisol peaked at day 28 under 5% FBBC (24.20 mg kg⁻¹), while the Entisol control showed a high transient value at day 56, confirming that time-dependent changes were not controlled by amendment rate alone.

3.4 pH response was buffered by soil type

Soil pH response was non-uniform (Fig. 4). Across the incubation, FBBC caused only small mean pH shifts in Vertisol and Entisol, but increased pH more clearly in Aridisol. This reflects the lower buffering capacity of the sandy material compared with the clay-rich Vertisol. Therefore, the alkaline character of FBBC did not translate into a uniform alkalinization effect across soils.

3.5 EC and SAR revealed different types of chemical risk

EC response was soil-specific (Fig. 5). Mean EC changed little in Vertisol and declined slightly in Entisol under FBBC addition, but increased by 27.3% in Aridisol at the 5% rate (Table 5). This indicates that the sandy soil carried the clearest salinity signal when exposed to the higher rate of an Olsen-P-rich and salt-bearing amendment.

SAR response showed a different pattern (Fig. 6). The highest absolute SAR values occurred in Vertisol, where the 5% rate increased mean SAR by 59.5% across incubation. In Entisol and Aridisol, relative SAR increases were sometimes large but absolute SAR values remained much lower than in Vertisol. These results show that the low SAR of FBBC reduced direct sodium burden, but did not remove the need for soil-specific sodicity screening.

3.6 Integrated treatment effects, temporal peaks and nutrient–risk relationships

The integrated treatment summaries showed clear differences among soils, FBBC rates and incubation times (Tables 5–7). Across the 112-day incubation, FBBC increased mean available P in all three soil materials. In the Aridisol, available P increased by 116.30% at 2.5% FBBC and by 138.68% at 5% FBBC relative to the corresponding control. In the Vertisol, available P increased by 72.95% at 2.5% FBBC and by 107.96% at 5% FBBC. The Entisol showed smaller increases, with available P rising by 31.38% at 2.5% FBBC and by 60.39% at 5% FBBC.

EC and SAR responses differed among soils and amendment rates (Table 5). Mean EC changed only slightly in the Vertisol, with a 0.16% increase at 2.5% FBBC and a 5.71% decrease at 5% FBBC. In the Entisol, EC declined by 9.67% and 8.78% under 2.5% and 5% FBBC, respectively. In the Aridisol, EC declined by 7.81% at 2.5% FBBC but increased by 27.33% at 5% FBBC. SAR increased in all amended treatments, with the largest absolute SAR values recorded in the Vertisol. Relative SAR increases were 40.09% and 59.53% in the Vertisol, 83.70% and 160.74% in the Entisol, and 42.50% and 79.14% in the Aridisol under 2.5% and 5% FBBC, respectively.

Time-specific summaries showed that peak available P occurred at different incubation times depending on soil and treatment (Table 6). In the Vertisol, the highest available P values under FBBC occurred at day 56, reaching 19.73 mg kg⁻¹ at 2.5% FBBC and 20.23 mg kg⁻¹ at 5% FBBC. In the Entisol, FBBC-treated soils reached their peaks earlier, at day 7, with 14.13 mg kg⁻¹ under 2.5% FBBC and 16.43 mg kg⁻¹ under 5% FBBC. In the Aridisol, both amended treatments peaked at day 28, reaching 20.53 mg kg⁻¹ at 2.5% FBBC and 24.20 mg kg⁻¹ at 5% FBBC. By day 112, available P remained above the corresponding control in all FBBC-amended soils.

The replicate-matched correlation matrix showed positive associations among available P, pH, EC and SAR (Table 7). Available P was weakly correlated with pH ($r = 0.206$, $p = 0.0047$), moderately correlated with EC ($r = 0.346$, $p < 0.001$) and moderately correlated with SAR ($r = 0.409$, $p < 0.001$). Stronger correlations were observed among the chemical risk indicators, particularly EC and SAR ($r = 0.793$, $p < 0.001$), pH and SAR ($r = 0.738$, $p < 0.001$), and pH and EC ($r = 0.624$, $p < 0.001$). These correlations describe co-variation among measured variables across the full replicate-level dataset.

Together, Tables 5–7 provide the numerical basis for the integrated nutrient–risk assessment. Table 5 summarizes mean treatment effects across the full incubation period, Table 6 identifies treatment-specific available P peaks and day-112 values, and Table 7 shows the direction and strength of associations among available P, pH, EC and SAR. The heatmap and nutrient–risk matrix presented in Figs. 7 and 8 visualize these treatment-level patterns.

Table 5
Soil-specific mean treatment effects across the 112-day incubation

Soil material	FBBC rate	Available P mean (mg kg ⁻¹)	P change (%)	pH mean	pH change (%)	EC mean (dS m ⁻¹)	EC change (%)	SAR mean	SAR change (%)
Vertisol	Control	7.78	0.00	8.92	0.00	0.88	0.00	7.42	0.00
	2.5%	13.46	72.95	8.98	0.73	0.89	0.16	10.40	40.09
	5%	16.18	107.96	8.93	0.20	0.83	-5.71	11.84	59.53
Entisol	Control	7.24	0.00	8.12	0.00	0.32	0.00	0.64	0.00
	2.5%	9.51	31.38	8.17	0.55	0.29	-9.67	1.18	83.70
	5%	11.61	60.39	8.12	-0.02	0.29	-8.78	1.68	160.74
Aridisol	Control	4.47	0.00	8.07	0.00	0.16	0.00	1.46	0.00
	2.5%	9.67	116.30	8.36	3.65	0.15	-7.81	2.08	42.50
	5%	10.67	138.68	8.49	5.22	0.20	27.33	2.62	79.14

Table 6
Time-specific available P peaks and day-112 values

Soil material	FBBC rate	Peak day	Peak available P (mg kg ⁻¹)	Peak SD	Day-112 available P (mg kg ⁻¹)	Day-112 SD
Vertisol	Control	28	14.27	1.66	12.90	2.00
	2.5%	56	19.73	0.67	17.43	1.47
	5%	56	20.23	2.34	16.37	0.32
Entisol	Control	56	16.97	1.05	11.10	1.42
	2.5%	7	14.13	0.23	13.23	0.40
	5%	7	16.43	0.93	15.13	0.97
Aridisol	Control	56	7.17	1.15	2.13	0.91
	2.5%	28	20.53	1.42	7.67	0.42
	5%	28	24.20	1.40	18.20	1.00

Table 7
Pearson correlation matrix for replicate-matched available P, pH, EC and SAR values

Variable	Available P	pH	EC	SAR
Available P	1.000	0.206	0.346	0.409
pH	0.206	1.000	0.624	0.738
EC	0.346	0.624	1.000	0.793
SAR	0.409	0.738	0.793	1.000

Note. Correlations were calculated using replicate-matched observations (n = 188). Significance levels were: available P–pH, $p = 0.0047$; available P–EC, $p < 0.001$; available P–SAR, $p < 0.001$; pH–EC, $p < 0.001$; pH–SAR, $p < 0.001$; EC–SAR, $p < 0.001$.

The P-gain heatmap (Fig. 7) and nutrient–risk matrix (Fig. 8) extend this interpretation visually by showing where P enrichment was achieved without a parallel increase in EC. The 2.5% FBBC treatment generally occupied a more conservative nutrient–risk position, while 5% FBBC produced larger P gains but required closer monitoring, particularly for EC in Aridisols and SAR in Vertisols.

4. Discussion

4.1 Fishbone biochar as a concentrated circular phosphorus source

The corrected Olsen-P concentration of FBBC (4999 mg kg⁻¹) is central to understanding the phosphorus response observed in this study. This value identifies FBBC as a concentrated calcium-bearing phosphorus amendment capable of supplying a large extractable P pool to the soil system.

At the 2.5% and 5% application rates, the theoretical Olsen-P inputs were approximately 125 and 250 mg P kg⁻¹ soil, respectively. These inputs were far higher than the amount recovered later as soil Olsen-P during incubation. This difference is important because it shows that the added P was not simply transferred from FBBC to the soil extract in a direct one-to-one manner. Once mixed with soil, the released P entered a chemically active system controlled by soil buffering, calcium-phosphate dissolution, sorption onto mineral surfaces, precipitation reactions and time-dependent re-equilibration.

The measured Olsen-P response therefore represents the net extractable fraction remaining after soil reactions acted on FBBC-derived P. The gap between theoretical P input and recovered soil Olsen-P is therefore an important part of the interpretation. It confirms that FBBC supplied a large extractable P source, but the final available pool depended strongly on the receiving soil and its capacity to retain, transform or re-precipitate phosphorus. This behaviour is consistent with known phosphorus reactions in alkaline and calcareous soil systems, where phosphate availability is regulated by calcium activity, sorption processes and the formation of less soluble Ca-P phases (Olsen et al., 1954; Lindsay, 1979;

Barrow, 1983; Frossard et al., 2000; Hinsinger, 2001; Sparks, 2003; Syers et al., 2008; Siebers & Leinweber, 2013; Amin, 2024).

Table 8

Literature context for phosphorus concentrations in fishbone, bone char and related calcium-phosphate materials

Study	Material	Thermal process	P indicator	Reported P concentration	Relevance to the present study
Present study	Nile fishbone biochar	Traditional low-oxygen kiln, approximately 2 h	Olsen-extractable P	4999 mg kg ⁻¹	Confirms a large extractable P pool in locally produced FBBC.
Piccirillo et al. (2017), summarized by Zhang et al. (2023)	Cod fish bone biochar	Pyrolysis at 600 and 1000°C	Total P	12.5–14.5% P, equivalent to 125,000–145,000 mg kg ⁻¹	Shows that thermally treated fish bones can retain large total P reserves.
Carella et al. (2021)	Sardinella aurita fish bones	Calcination at 300, 600 and 900°C	P-rich calcium-phosphate material	Up to approximately 18 wt.% P	Supports fish bones as calcium-phosphate feedstocks for fertilizer-like materials.
Zhang et al. (2023)	Fish bone ash	Ashing or combustion	Total P	170 g kg ⁻¹ , equivalent to 170,000 mg kg ⁻¹	Shows the high total P reserve in fish bone ash.
Warren et al. (2009), summarized by Zhang et al. (2023)	Cattle bone char	Heat-treated animal bone char	Total P and extractable P fractions	13.4% total P; 11.5% neutral ammonium citrate-extractable P; approximately 1500 mg kg ⁻¹ Olsen-P; 244 mg kg ⁻¹ water-extractable P	Shows that only part of bone-char P is recovered by extractants.
Zhang et al. (2023)	Fishery waste and by-products	Review of nutrient-recovery technologies	Nutrient recovery potential	Fish bone biochars reported with 9.2–14.5% P, depending on pyrolysis temperature	Places FBBC within fishery-waste nutrient recovery literature.

Note. Values are not directly interchangeable because the studies reported different P indicators, including total P, Olsen-P, neutral ammonium citrate-extractable P and water-extractable P. Total P reflects the bulk phosphorus reserve, whereas Olsen-P and water-extractable P represent more specific extractable pools. The table is used for contextual comparison, not for ranking all materials on a single availability scale.

Table 8 places the Olsen-P concentration measured in the present FBBC within the broader literature on fishbone, bone char and related calcium-phosphate materials. The comparison shows that thermally treated fish bones and fish bone ash can contain large total P reserves, often exceeding 100,000 mg kg⁻¹. These values, however, represent bulk P pools and should not be interpreted as directly available P. The present FBBC contained 4999 mg kg⁻¹ Olsen-extractable P, which confirms its value as a concentrated extractable P source while also explaining why soil buffering, sorption and calcium-phosphate re-equilibration controlled the amount recovered as soil Olsen-P.

4.2 Geochemical basis of phosphorus release and retention

The phosphorus response to FBBC is better explained by calcium-phosphate geochemistry than by a conventional biochar mechanism. Unlike plant-derived biochars, fishbone-derived chars are expected to contain calcium-phosphate minerals, particularly hydroxyapatite-like phases, together with carbonized organic residues and ash minerals. During thermal treatment, these bone-derived minerals may become more concentrated as organic matter is lost, and their subsequent behaviour in soil is controlled by dissolution, Ca²⁺ activity, pH, carbonate chemistry and sorption onto mineral surfaces (Lindsay, 1979; Lindsay et al., 1989; Frossard et al., 2000; Sparks, 2003; Schütze et al., 2020; Amin, 2024).

In the present study, mineral phases were not directly identified by XRD, FTIR or SEM. Therefore, the proposed mechanism should be interpreted cautiously as a geochemical explanation supported by the fishbone feedstock, the high Olsen-P content of FBBC and the observed soil response, rather than as direct mineralogical proof. Under alkaline dryland conditions, orthophosphate released from a bone-derived amendment does not remain entirely in solution. Part of it can be adsorbed onto clay and carbonate surfaces, while another part can re-precipitate as less soluble calcium-phosphate forms. These reactions are especially important where soil pH is high and Ca²⁺ activity is sufficient to favour Ca-P re-equilibration (Lindsay, 1979; Barrow, 1983; Lindsay et al., 1989; Hinsinger, 2001; Sparks, 2003; Syers et al., 2008).

This mechanism helps explain the strong but incomplete recovery of FBBC-derived P in the Vertisol. The 5% FBBC treatment increased mean available P in the Vertisol by 108.0%, despite the clay-rich matrix and its high capacity to retain phosphate. The large Olsen-P input from FBBC likely exceeded the immediate sorption demand of the clay and carbonate surfaces, allowing a larger fraction of orthophosphate to remain Olsen-extractable. This does not mean that the P-fixation capacity of the Vertisol was removed. Rather, the system was temporarily shifted toward a larger extractable P pool before part of the released phosphate was retained, transformed or re-precipitated into less extractable Ca-P forms.

The lower recovery of soil Olsen-P relative to the theoretical P input is therefore chemically meaningful. At 2.5% and 5% FBBC, the theoretical Olsen-P inputs were approximately 125 and 250 mg P kg⁻¹ soil, respectively, yet the measured increases in soil Olsen-P were much smaller. This gap indicates that FBBC supplied a strong extractable P source, but the receiving soil rapidly moderated its expression through sorption and precipitation reactions. In localized microsites near FBBC particles, high phosphate activity may favour transient calcium-phosphate phases such as dicalcium phosphate-like forms, whereas the

broader alkaline soil environment may progressively drive part of the P pool toward more stable apatite-like forms. Similar kinetic behaviour has been reported for bone char and hydroxyapatite, where P release is slow, soil-dependent and strongly affected by particle size, organic acids and solution chemistry (Warren et al., 2009; Schütze et al., 2020; Amin, 2024).

FBBC introduced a concentrated calcium-phosphate source into three chemically different soil matrices. The final Olsen-P response represented the balance among P release from FBBC, sorption onto soil surfaces, Ca-P precipitation, carbonate buffering and time-dependent re-equilibration. This explains why the same amendment produced different responses in Vertisol, Entisol and Aridisol, and why high Olsen-P input did not translate into full quantitative recovery as soil Olsen-P.

4.3 Temporal trajectory of phosphorus release and re-equilibration

The 112-day incubation was important because it showed that the FBBC effect was not a single, immediate fertilizer response. Available P changed through time, and each soil followed a different release pattern. The Aridisol showed its strongest P pulse at day 28 under 5% FBBC, the Vertisol reached its maximum at day 56, and the Entisol showed early peaks under the amended treatments. This confirms that incubation time was not a secondary factor; it was a key part of the soil–amendment response.

The pattern suggests two linked stages. The first stage was a rapid release or extraction of readily accessible FBBC-associated P after the amendment came into contact with the soil. This early phase was most visible in the Aridisol, where low clay content and weak buffering allowed a sharper increase in Olsen-P. The second stage involved slower re-equilibration within the soil matrix. During this phase, part of the released phosphate was likely re-adsorbed onto mineral surfaces, retained by carbonate and clay fractions, or converted into less extractable calcium-phosphate forms. This explains why available P did not continue to rise linearly up to day 112.

The delayed peak in the Vertisol is consistent with stronger buffering and slower internal redistribution in the clay-rich soil. In this soil, phosphate released from FBBC was probably retained and re-equilibrated more gradually, allowing Olsen-P to remain elevated for a longer period before declining. By contrast, the sharper Aridisol peak at day 28 suggests faster release and weaker retention. Under field conditions, this type of response could be agronomically useful in the short term, but it also raises concern that part of the soluble P pulse may become mobile if water movement occurs through the sandy profile.

The Entisol response occupied an intermediate position. The amended treatments peaked early, while the control showed a transient increase at day 56. This indicates that time-dependent Olsen-P dynamics were not controlled by FBBC addition alone. Internal soil processes, including desorption of native P, microbial activity, carbonate buffering and changing solution chemistry, may also have contributed to the temporal pattern.

Because the experiment was conducted in closed incubation pots without leachate collection, any decline in Olsen-P after a peak should not be interpreted as measured P loss. A more cautious interpretation is

that part of the initially extractable P became less recoverable by Olsen extraction as the soil–FBBC system approached a new chemical equilibrium. This temporal behaviour agrees with previous work showing that P release from bone char, hydroxyapatite and recycled calcium-phosphate fertilizers is often governed by slow dissolution, diffusion and re-precipitation rather than instantaneous solubility (Barrow, 1983; Frossard et al., 2000; Hinsinger, 2001; Warren et al., 2009; Schütze et al., 2020; Amin, 2024).

4.4 The Aridisol response and phosphorus mobility risk

Phosphorus is usually considered poorly mobile in alkaline dryland soils because released orthophosphate is rapidly adsorbed onto mineral surfaces or precipitated as calcium-phosphate phases. This behaviour is expected in clay-rich and calcium-buffered soils, such as the Vertisol used in this study, where abundant colloidal surfaces and high buffering capacity can retain a large proportion of added P (Lindsay, 1979; Sims et al., 1998; Shen et al., 2011).

The Aridisol response, however, represents an important exception to this general rule. The 5% FBBC treatment introduced a very large Olsen-P input from a material containing 4999 mg kg⁻¹ Olsen-extractable P. In the sandy Aridisol, the limited clay content and weak buffering capacity mean that fewer sorption sites were available to retain the released orthophosphate. Once these sites became saturated, part of the added P likely remained in more soluble or weakly retained forms within the soil solution. This helps explain the sharp increase in available P observed in the Aridisol and its earlier peak compared with the clay-rich Vertisol.

This result has a clear environmental implication. Under field conditions, a sandy soil receiving a high rate of an Olsen-P-rich amendment may not behave like a typical P-fixing dryland soil. If water movement occurs through the profile, the excess weakly retained P could become mobile and move downward beyond the amended layer. Previous work has shown that P leaching can increase once soil P saturation exceeds the retention capacity of the soil, especially in coarse-textured or weakly buffered systems (Heckrath et al., 1995; Sims et al., 1998; Yao et al., 2012). In such cases, an amendment that improves P availability can also create a potential risk of groundwater or downstream eutrophication if applied at excessive rates (Carpenter et al., 1998).

The present incubation did not measure leachate P, so this interpretation should be treated as a risk signal, not as direct evidence of P loss. Nevertheless, the Aridisol response is strong enough to justify caution. For sandy dryland soils, FBBC should not be applied at high rates without leachate monitoring, crop uptake assessment and field validation. The safer management approach is to begin with conservative rates, such as 2.5%, and evaluate whether P gain can be achieved without creating a parallel risk of P mobility.

4.5 Dose response and the value of the 2.5% rate

The dose response showed that the highest FBBC rate did not always provide the most balanced outcome. The 5% rate generally increased available P more than the 2.5% rate, but the increase was not proportional in all soils or at all incubation times. This is an important management point. A higher

amendment rate may deliver more P, but it can also reduce the chemical safety margin if it increases EC, SAR or potential P mobility.

For this reason, the 2.5% rate has practical value. It produced a clear P gain in all three soils while causing smaller shifts in EC and SAR than the 5% treatment in most cases. This makes it a more defensible screening rate for greenhouse or early field validation, particularly where salinity, sodicity or leaching risk already limits soil performance. In dryland soils, the best amendment rate is not necessarily the one that produces the highest extractable P value. It is the rate that improves nutrient availability without creating a second constraint.

This interpretation is consistent with the broader biochar and recycled-nutrient literature. Biochar can increase soil P availability, but the magnitude of response depends on feedstock, pyrolysis conditions, soil properties and application rate. Reviews and meta-analyses have shown that biochar effects on available P vary widely across soils, and that rate selection should consider nutrient supply and environmental risk together rather than nutrient enrichment alone (Taghizadeh-Toosi et al., 2012; Parvage et al., 2013; Glaser & Lehr, 2019; Li et al., 2019). The present results support the same principle for fishbone biochar: the agronomically useful rate is the rate that recovers P efficiently while keeping EC, SAR and P mobility within acceptable limits.

4.6 Salinity and sodicity trade-offs

The salinity and sodicity response cannot be interpreted simply by stating that FBBC itself had a low SAR. Although the amendment did not add a large direct sodium burden, the receiving soil controlled the final SAR response. This was most evident in the Vertisol, which had the highest baseline sodium risk and showed the highest absolute SAR values after amendment. In contrast, the Entisol and Aridisol showed lower absolute SAR values, even when their relative changes appeared large.

This distinction between absolute risk and relative change is important. A large percentage increase in SAR may remain agronomically modest if the starting value is low. Conversely, a smaller relative change may be more serious in a soil that already has elevated SAR. The Vertisol therefore requires closer sodicity monitoring, not because FBBC was intrinsically sodic, but because the soil already had a chemical background that made sodium-related structural risk more relevant.

EC followed a different pattern. The strongest EC concern appeared in the Aridisol at the 5% rate, where the sandy texture and weak buffering capacity made the soil more sensitive to soluble salt accumulation. This shows that the same amendment can create different risk signals depending on soil texture and baseline chemistry. In clay-rich soils, SAR may be the more important constraint. In sandy soils, EC and soluble P mobility may require closer attention.

These findings agree with the established understanding of salt-affected soils. Soil structure and hydraulic behaviour are controlled by the interaction between sodium hazard and electrolyte concentration, not by SAR alone. Classic work showed that permeability and clay dispersion depend on both exchangeable sodium and solution salinity, while later studies confirmed that clay type, clay content

and electrolyte concentration strongly regulate hydraulic conductivity in sodic systems (Quirk & Schofield, 1955; Frenkel et al., 1978; Shainberg & Letey, 1984; Rengasamy, 2010, 2016). For biochar use in salt-affected soils, this means that amendment performance must be tested within each soil context rather than assumed from amendment chemistry alone (Al-Wabel et al., 2013; Chaganti & Crohn, 2015; Dahlawi et al., 2018).

4.7 Practical implications for dryland soil management

The practical value of FBBC lies in converting a locally available fishbone residue into a concentrated calcium–phosphorus amendment. This is particularly relevant to dryland agriculture, where low available P, alkaline soil chemistry and fertilizer cost can limit soil productivity. The literature comparison in Table 8 shows that bone-derived products may contain large P reserves, but their agronomic value depends on the extractable P fraction and on the capacity of the receiving soil to retain, transform or release that fraction.

The present results suggest different management implications for the three soil materials. In low-P sandy Aridisols, FBBC can sharply increase available P, but this response may also create a risk of P mobility if high rates are used or if strong water movement occurs after application. In clay-rich Vertisols, FBBC can enrich Olsen-P even under strong buffering conditions, but SAR should be monitored where baseline sodicity is already high. In Entisols, FBBC produced a more balanced response, with clear P enrichment and relatively modest EC change.

The practical recommendation is therefore to apply a screen-first approach. Before field-scale use, FBBC should be chemically characterized, especially for Olsen-P, EC, soluble cations and SAR. The receiving soil should also be tested for texture, pH, EC, SAR, carbonate content and initial available P. Application should begin with a conservative rate, such as 2.5%, followed by greenhouse validation and then small field plots. The P response should be interpreted together with EC, SAR and possible P mobility, rather than as an isolated nutrient-gain result.

This approach treats FBBC as a promising circular phosphorus material, but not as a universal amendment. Its value depends on matching the amendment rate with soil buffering capacity, salinity status, sodicity risk and drainage behaviour. Used in this way, FBBC can support nutrient recycling in dryland soils while reducing the chance that P enrichment creates a new chemical or environmental constraint. The practical screening implications of these findings are summarized in Table 9.

Table 9
Proposed screening framework for soil-specific use of fishbone biochar in dryland soils

Screening step	Indicator to assess	Interpretation	Recommended management response
Baseline soil P status	Olsen-P below the locally defined sufficiency threshold	The soil is likely to respond to P addition, especially where native available P is low and crop demand is high.	Prioritize FBBC testing in low-P soils, but do not assume agronomic response without plant-based validation.
FBBC extractable P	Olsen-extractable P of FBBC; 4999 mg kg ⁻¹ in the present study	FBBC should be treated as a concentrated extractable-P source, not only as a general soil conditioner.	Classify FBBC as a fertilizer candidate and calculate application rates on a P-loading basis before soil application.
Amendment rate	2.5% and 5% w/w in the present study	The higher rate increased available P more strongly, but it also narrowed the chemical safety margin in some soils.	Use 2.5% as an initial screening rate before testing higher rates under greenhouse or field conditions.
Soil texture and buffering capacity	Clay-rich Vertisol versus sandy Aridisol	Soil texture controls P retention, salinity response, sodicity risk and possible P mobility.	Interpret FBBC performance by soil type rather than by amendment rate alone.
EC response	EC ratio relative to the unamended control	An EC increase indicates possible salinity pressure, especially where the soil has weak buffering capacity.	Monitor EC after application, with special caution in sandy soils and high FBBC rates.
SAR response	High baseline SAR or post-amendment SAR increase	Sodic risk depends on the receiving soil, even when the amendment itself has low SAR.	Avoid untested high-rate application in sodium-sensitive Vertisols and monitor SAR before scaling.
P mobility risk	High Olsen-P input in coarse-textured soil	Weak P retention may allow part of the added P to remain mobile under water movement.	Include leachate-P monitoring before recommending FBBC for sandy soils at high application rates.
Greenhouse and field validation	P gain without unacceptable EC, SAR or leachate-P increase	The treatment is promising only when nutrient benefit is achieved without creating a new chemical or environmental constraint.	Proceed stepwise from laboratory screening to greenhouse trials and then small field plots, including plant uptake, biomass, EC, SAR and leachate-P measurements.
<p>Note. This screening framework is intended to guide cautious use of FBBC as a circular phosphorus amendment. The framework does not replace crop-response trials. Field recommendation should be based on soil testing, amendment characterization, plant uptake, biomass response and monitoring of EC, SAR and potential P mobility.</p>			

This screening framework translates the incubation results into a practical decision pathway for dryland soil management. The central message is that FBBC should not be applied only on the basis of its high

Olsen-P concentration. Its use should begin with soil and amendment screening, followed by conservative-rate testing and staged validation. The 2.5% rate is the most defensible starting point because it produced substantial P enrichment while generally maintaining a wider chemical safety margin than the 5% rate. Higher rates may be useful in specific low-P soils, but they require closer monitoring of EC, SAR and potential P mobility, particularly in sandy Aridisols and sodium-sensitive Vertisols.

5. Study scope and future validation

This study was designed as a controlled incubation experiment to examine the chemical response of three contrasting dryland soils to locally produced fishbone biochar (FBBC). The laboratory design made it possible to isolate the effects of soil type, amendment rate and incubation time under comparable moisture and temperature conditions. This was important because the main objective was not to issue a direct fertilizer recommendation, but to establish a soil-process screening framework that can guide the next stages of greenhouse and field evaluation.

The results should therefore be interpreted within this scope. The incubation data provide strong evidence that FBBC can supply a large Olsen-extractable P pool and that the response differs markedly among Vertisol, Entisol and Aridisol. However, the study did not measure crop uptake, biomass production, root response or leachate chemistry. For this reason, the findings should be treated as a controlled chemical assessment rather than a complete agronomic validation.

Future work should include greenhouse and field trials that measure plant P uptake, biomass response, root growth, phosphatase activity, microbial indicators and changes in P fractions through time. Leachate P, leachate EC and leachate SAR should also be measured, especially in sandy soils where the present results indicated a possible mobility risk under high FBBC loading. Longer-term studies are also needed to determine whether the initial P gain is sustained, stabilized into less available Ca-P forms or redistributed with salts during repeated wetting and drying cycles.

The FBBC material itself should also be characterized more fully. Future analyses should include ash content, total carbon, elemental composition, total P, P speciation, potentially toxic elements, X-ray diffraction, Fourier-transform infrared spectroscopy, scanning electron microscopy and surface area measurements. These analyses would clarify the mineral forms responsible for P release, the degree of transformation during thermal treatment and the possible presence of contaminants. They would also help link Olsen-P release to actual plant availability, which is the critical step before recommending field application (Nelson & Sommers, 1982; Cao et al., 2009; Quilliam et al., 2013; Bolan et al., 2014; Zheng et al., 2019; Amin, 2024).

The immediate contribution of this study is therefore not a universal recommendation for FBBC use. Its value lies in showing that fishbone residues can be converted into an Olsen-P-rich calcium-phosphorus amendment, but that its benefits and risks depend strongly on the receiving soil. In practical terms, FBBC should move forward through a stepwise validation pathway: material characterization, soil screening, conservative-rate testing, greenhouse trials and then field plots with plant uptake and leachate

monitoring. This sequence allows the amendment to be evaluated as a circular phosphorus resource while avoiding premature recommendations that could create salinity, sodicity or P-mobility risks.

6. Conclusions and management implications

This study demonstrates that Nile fishbone biochar can act as a concentrated calcium-bearing phosphorus amendment for dryland soils. Its corrected Olsen-extractable P concentration of 4999 mg kg⁻¹ shows that the material should not be viewed only as a general biochar conditioner. It has the chemical character of a recycled phosphorus source, with clear potential to convert fishbone residues from an unmanaged organic waste into a locally useful nutrient resource.

Across the 112-day incubation, FBBC increased soil available P in the Vertisol, Entisol and Aridisol. The response, however, was strongly soil-specific. The sandy Aridisol showed the strongest relative increase because of its low initial P status and weak buffering capacity. The clay-rich Vertisol showed a strong absolute P response, indicating that the high Olsen-P input from FBBC was able to raise extractable P even in a soil with greater retention capacity. The Entisol showed a more balanced response, with clear P enrichment and relatively modest EC change.

The results also show that FBBC performance cannot be interpreted as a simple dose effect. Although the 5% rate generally supplied more available P than the 2.5% rate, the increase was not always proportional and was not always the safest option. The measured soil Olsen-P remained far below the theoretical P added at both rates, confirming that the final extractable P pool was controlled by soil buffering, phosphate sorption, calcium-phosphate reactions and time-dependent re-equilibration. This distinction is important because it separates FBBC as a concentrated P source from the actual amount of P that remains extractable in each soil.

The chemical safety findings are equally important. FBBC itself had low SAR, but the receiving soil controlled the final sodicity response. The Vertisol requires the greatest caution because of its high baseline SAR and stronger post-amendment SAR values. The Aridisol requires closer monitoring of EC and potential P mobility, especially at the 5% rate, because sandy soils have lower retention capacity and a greater chance of downward P movement under leaching conditions. The Entisol appeared to offer the most balanced nutrient–risk response within the conditions of this incubation study.

The most defensible management implication is therefore a screen-first approach. FBBC should be considered first in soils where available P is limiting, but application should begin with conservative rates, especially around 2.5% w/w, before testing higher rates. Any recommendation should be based not only on P gain, but also on EC, SAR, soil texture, baseline sodicity and possible P mobility. Greenhouse and field validation are essential before recommending broad field-scale use.

In practical terms, FBBC is a promising circular phosphorus material, but not a universal amendment. Its value depends on matching the amendment rate to the receiving soil. When used through soil testing, conservative dosing and staged validation, fishbone residues can become a locally relevant phosphorus-

recycling resource for dryland phosphorus management while reducing the risk of salinity, sodicity or P-leaching constraints.

Declarations

Ethics approval and consent to participate

Not applicable.

Clinical trial number:

not applicable.

Consent for publication

Not applicable.

Permission statement

Fishbone residues used in this study were obtained as post-consumer market waste from commercially available Nile fish sold for food purposes. No live animals were handled, captured, sacrificed, or experimentally treated by the authors. The study did not involve animal experimentation, field collection of wild animals, or sampling from protected wildlife. The fishbone material was used only as discarded organic residue for biochar production.

Availability of data and materials

Data are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

J.E. conceptualized the study, supervised the experimental design, conducted the statistical analysis, interpreted the data and prepared the manuscript. R.A. conducted the laboratory incubation experiment, organized the raw data and contributed to the preliminary interpretation. Both authors read and approved the final manuscript.

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Figures

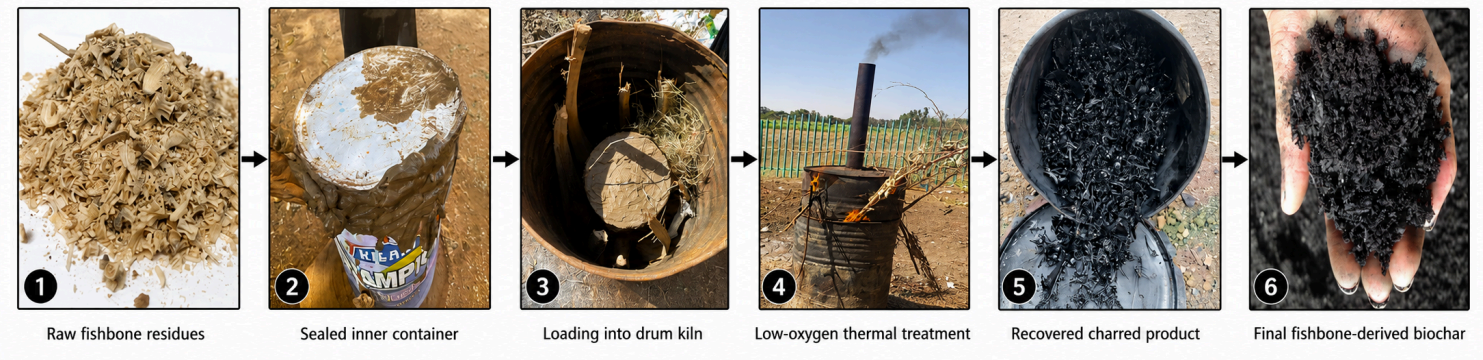


Figure 1

Preparation steps of fishbone biochar from fishbone residues, showing raw fishbone residues, sealing of the inner container, loading into the drum kiln, low-oxygen thermal treatment, recovery of the charred product and the final fishbone biochar.

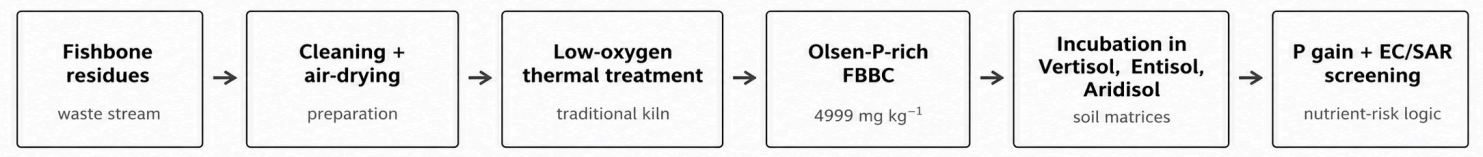


Figure 2

Conceptual framework and production pathway for fishbone biochar as a circular phosphorus source in dryland soils.

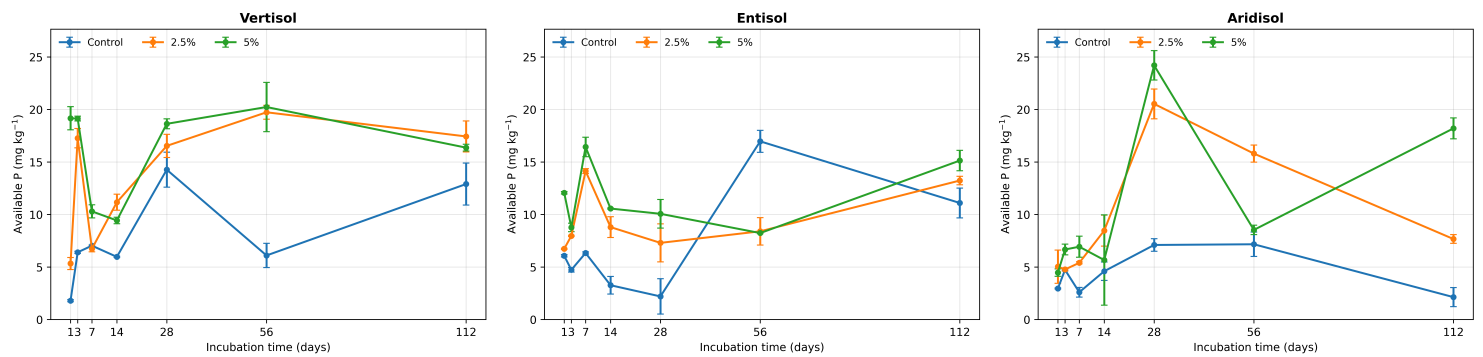


Figure 3

Available phosphorus dynamics during 112-day incubation in Vertisol, Entisol and Aridisol under control, 2.5% FBBC and 5% FBBC treatments. Values are means $\pm$ SD of three replicates.

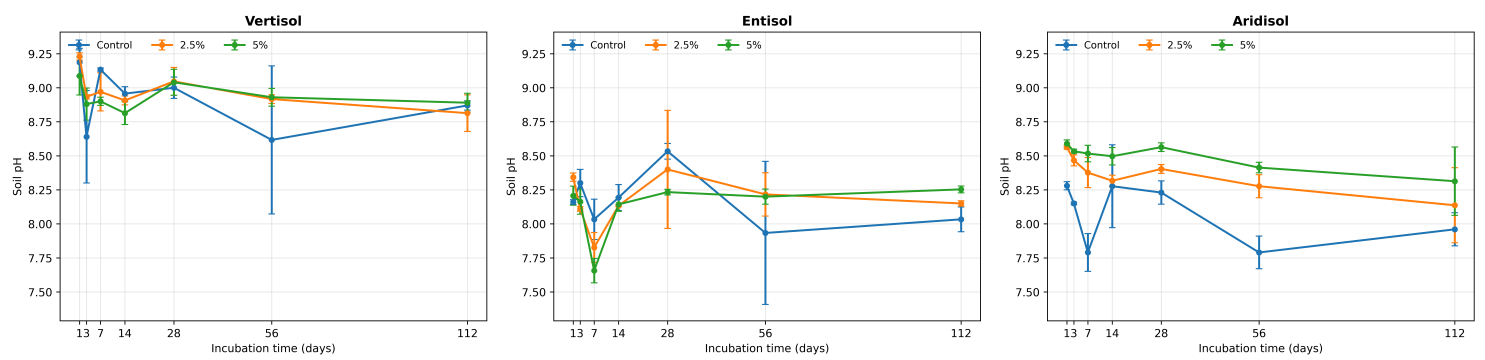


Figure 4

Soil pH response during 112-day incubation in Vertisol, Entisol and Aridisol under control, 2.5% FBBC and 5% FBBC treatments. Values are means $\pm$ SD of three replicates.

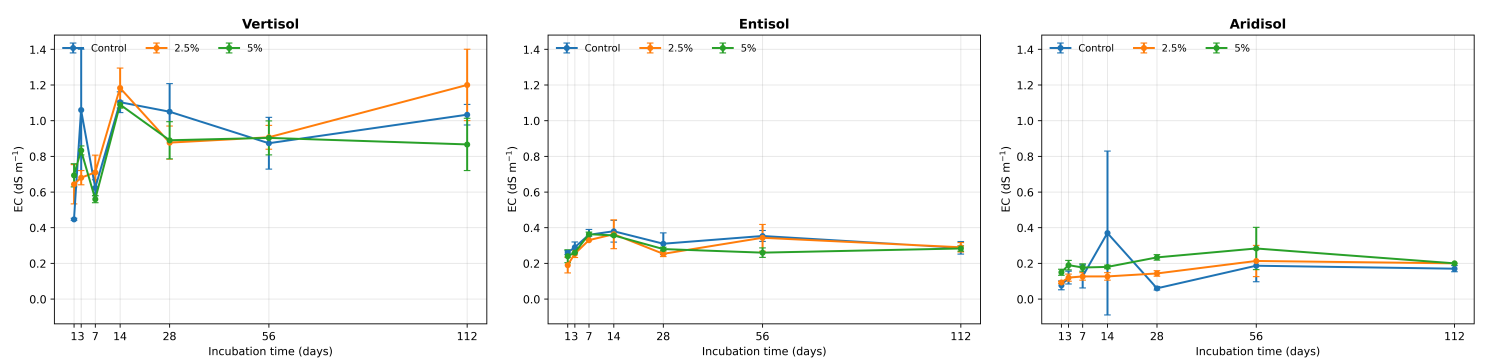


Figure 5

Electrical conductivity response during 112-day incubation in Vertisol, Entisol and Aridisol under control, 2.5% FBBC and 5% FBBC treatments. Values are means $\pm$ SD of three replicates.

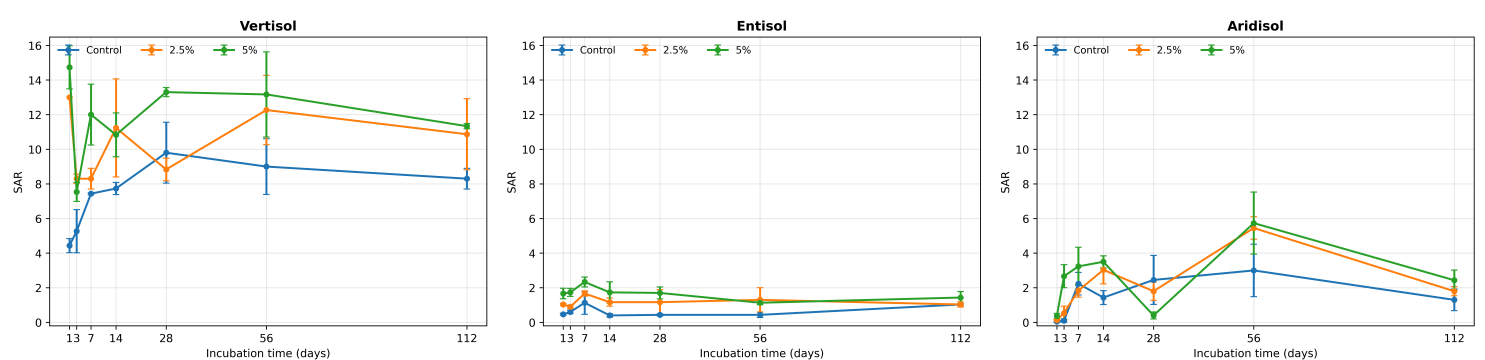


Figure 6

Sodium adsorption ratio response during incubation. Values are means $\pm$ SD of three replicates.

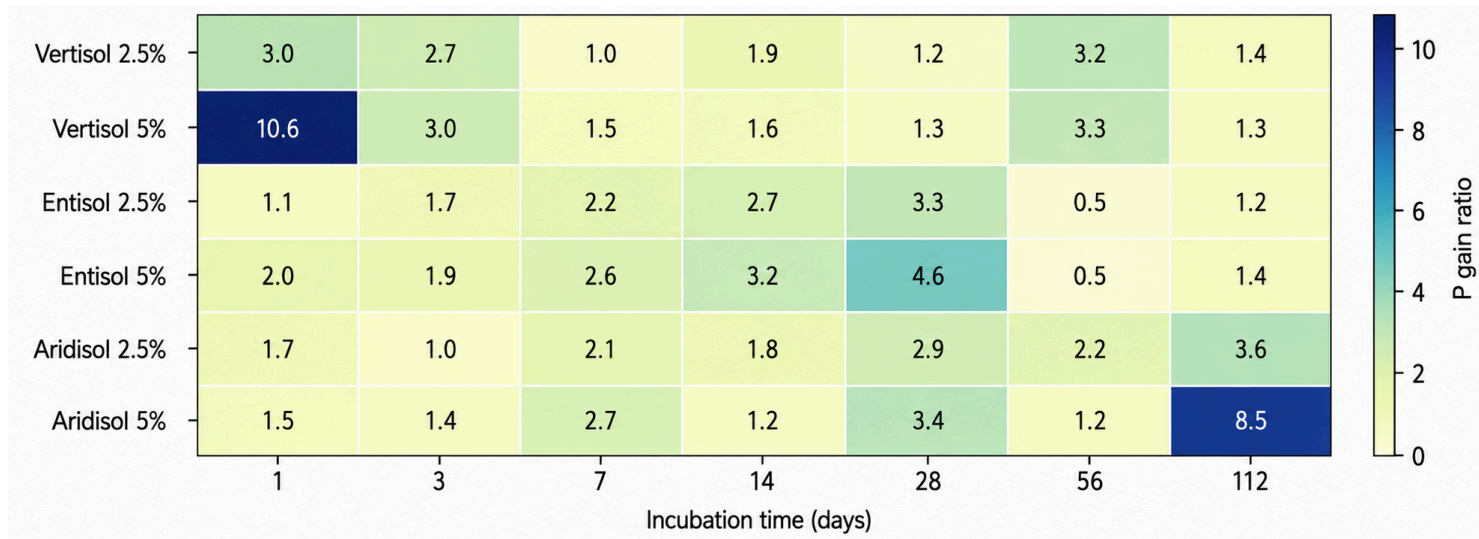


Figure 7

Heatmap of available P gain ratio relative to the corresponding control at each incubation time.

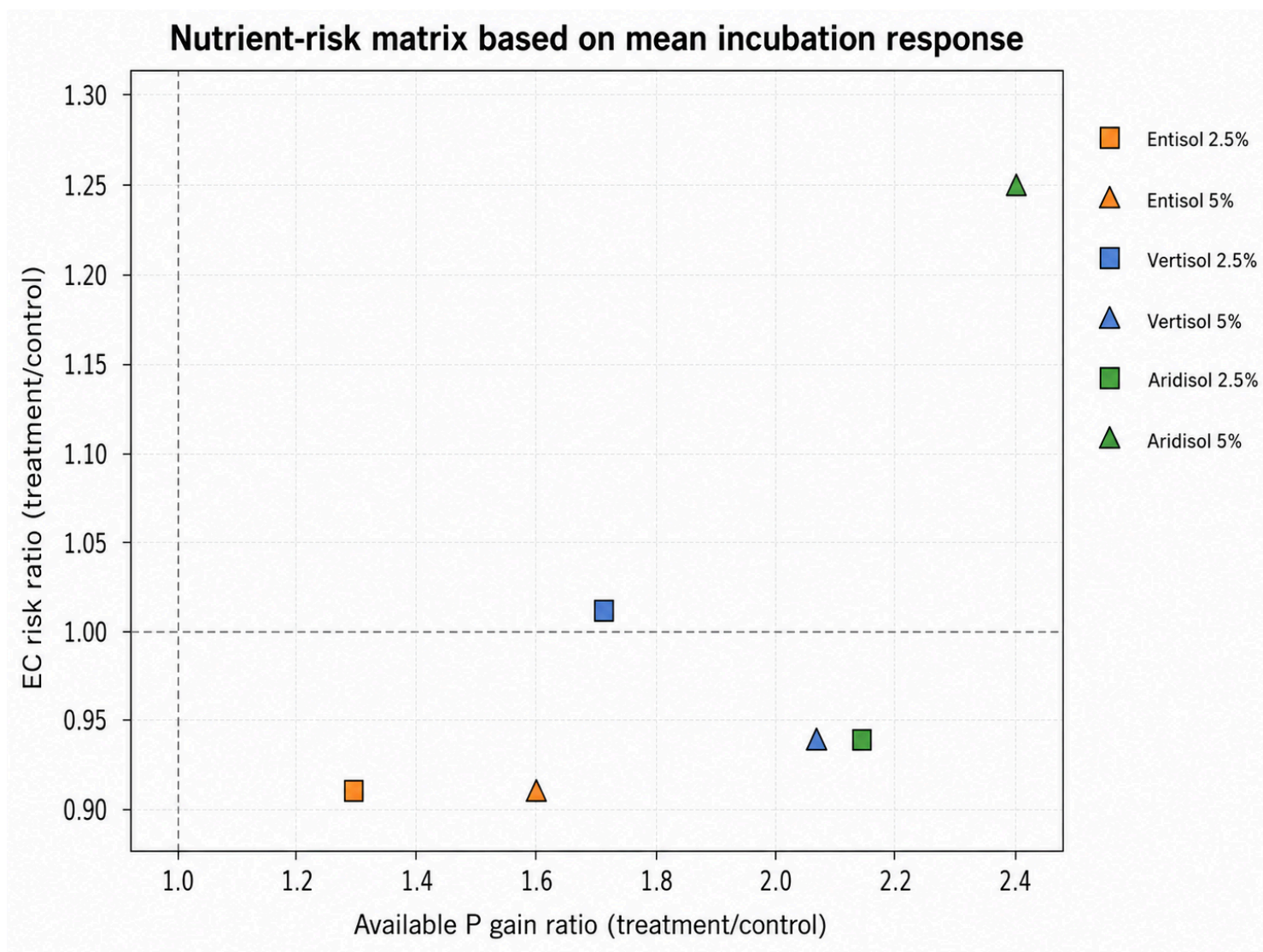


Figure 8

Nutrient–risk matrix linking available P gain with EC response under fishbone biochar amendment. Values represent mean treatment/control ratios across the 112-day incubation.