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Biochar

ORIGINAL RESEARCH

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Distinct forms of liquid biochar mineral complex fertilisers differently increase crop yield, nutrient balance and economic return

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Abstract

Sustaining crop yield is a growing challenge due to soil fertility loss and climate change. As a result, fertiliser application is increasing to sustain yield and counteract low fertiliser use efficiency. Developing nutrient-efficient fertilisers, for example by combining biochar with fertilisers, is thus crucially needed. In this context, the development of biochar-mineral complex (BMC) fertilisers into liquefied products suitable for broadacre application is highly innovative. This study aimed to explore the agronomic benefits and economic viability of four novel liquefied BMCs designed for application within a pasture cropping system. The different forms of developed BMCs included two non-enriched BMCs (BMC1 and BMC2) that were micronised using different techniques, a phosphorus (P)-enriched BMC (BMC3), and a nitrogen (N)-enriched BMC (BMC4), all applied both with- and without co-fertilisation. Soil biochemistry, plant NP uptake, NP balances, plant yield and cost–benefit were examined. Pasture yield was significantly higher using BMC1 and BMC3 with co-fertilisation than without, most likely due to improved P availability, as evidenced by positive P balances. Yield was significantly enhanced under BMC4 at 42.20 t ha^{-1}, compared with BMC1 at 21.90 t ha^{-1}, BMC2 at 19.41 t ha^{-1}, BMC3 at 25.81 t ha^{-1}, the fertilised control at 18.75 t ha^{-1} and non-fertilised control at 11.53 t ha^{-1}. Only BMC4 showed positive NP balances, suggesting that pasture did not absorb N and P from the existing soil reserve. Soil microbial composition and abundance were not affected by the applied BMC treatments in short term. The benefit–cost ratio ranged from 1.94 to 2.54, indicating economic viability of the BMC products and suggesting a great potential of biochar-based fertilisers for wide adoption to other crops.

Highlights

- Yield was significantly increased under N-enriched BMC (BMC4) compared with all other treatments.
- BMC4 showed positive NP balances, suggesting that plants did not mine N and P from the existing soil reserve.
- Pasture yield was significantly higher using BMC1 and BMC3 with co-fertilisation compared to without co-fertilisation.

Keywords Biochar micronisation, Nutrient balance, Nitrogen, Phosphorus, Pasture, Economic feasibility

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Graphical Abstract

Liquid biochar-based fertiliser **Harvest**

1 Introduction

Climate change and soil degradation are creating significant challenges to sustain crop productivity (Becker and Fanzo 2023). As a result, fertilisers are increasingly applied to improve crop yield; however, many fertilisers are not used efficiently by plants (Smith et al. 2022; Yang et al. 2024). It is estimated that up to 50% of applied nitrogen (N) and 80% of phosphorus (P) are not assimilated by the target plants and therefore become a source of environmental pollution due to run off and leaching (Adhikari et al. 2023; Govindasamy et al. 2023). Fertilisers can also negatively affect soil-microbe-plant systems by accelerating soil organic matter depletion and contributing to nutrient imbalance (Singh 2018; Zeng et al. 2023). Increased fertiliser applications may thus be counterproductive, reducing crop yield and increasing financial losses (Rickson et al. 2015; Omidvar et al. 2026). Therefore, there is a continued need to develop novel fertilisers that are nutrient-efficient, cost-effective, and environmentally friendly to ensure ongoing crop productivity and economic feasibility while minimising negative environmental impacts of modern farming systems.

Biochar is a carbon (C) rich soil amendment known for its potential to improve soil fertility and reduce reliance on conventional fertilisers (Asadyar et al. 2021; Joseph and Taylor 2024; Omidvar et al. 2026). Biochar reduces the leaching of vital plant nutrients and promotes nutrient sorption through enhanced exchange of positive ions in the soil and stimulation of microbial processes leading to increased crop yield (Bai et al. 2015, 2022, 2024; Farrar et al. 2021; Nguyen et al. 2017a, b; Zhang et al. 2018, 2024). However, applying biochar may not be economically viable due to the need of high application rates, unpredictable effects on crop yields, high freight costs and lack of wide accessibility (Joseph and Taylor 2024).

Biochar-based fertilisers have been developed for a variety of crops in granular or dry solid forms to act as slow-release fertilisers, increasing fertiliser use efficiency while reducing biochar application rates and associated costs (Joseph et al. 2013; Farrar et al. 2019, 2021; Trubenbacher et al. 2025). However, their effects on nutrient dynamics and yield have been mostly examined in pot studies (Joseph et al. 2013; Farrar et al. 2019, 2021; Trubenbacher et al. 2025). As fertilisers in liquid forms may increase crop yield more readily because they directly provide nutrients in the root zone or foliage, where they are promptly absorbed after application (Govil et al. 2024; Stamate et al. 2024), developing liquefied biochar-based fertilisers is a novel and promising approach to improving the nutrient use efficiency of the applied fertilisers. A wide range of biochar-based fertiliser formulations can be tailored to diverse cropping systems. Biochar mineral complex (BMC) is one type of biochar-based fertiliser created as a solid or granular form (Joseph and Taylor 2024). The process involves mixing a biochar feedstock with additional nutrient sources, such as animal manure, and incorporating minerals, metal oxides, and clays prior to pyrolysis (Joseph et al. 2013; Joseph and Taylor 2024). During this process, the specific biochar properties, time and temperature, and combination of specific ingredients, all contribute to affect soil–plant systems (Joseph et al. 2021). For example, adding clays such as kaolinite and bentonite increases the cation exchange capacity (CEC) of the BMC and the soil where it is applied, thereby increasing soil nutrient retention and availability (Huang and Hartemink 2020; Jing et al. 2022) and improving plant nutrient use efficiency (NUE) (Cassman et al. 2002; Omidvar et al. 2025). Micronisation has also shown to increase biochar surface area and improve fertiliser mobility within soil profiles (Wang et al. 2019), leading to improved fertiliser use efficiency. In liquefied BMC, biochar is micronised to a particle size of ≤50 µm, contributing to improve NUE (Joseph and Taylor 2024) and plant productivity, which is often limited by N and/or P availability (Seghouani et al. 2024). Therefore, liquefied BMCs may represent a viable solution to improve N and P use efficiency, enhancing crop yield while maintaining soil fertility.

Soil microorganisms play a crucial role in facilitating nutrient transformations and regulating soil ecosystem functions (Abujabhah et al. 2018; Mahala et al. 2020; Nguyen et al. 2018). Moreover, they constitute great biological indicators of soil health and plant production as they usually are quickly responsive to management treatments (Lehmann et al. 2020). Increased crop yield following fertiliser application has been well documented, but this may come at the expense of soil microbial diversity, due to soil acidification caused by fertilisation (Shen et al. 2016). Biochar has also shown to affect soil microbial composition and diversity (Li et al. 2018; Xu et al. 2018), suggesting that both fertiliser and biochar application could alter soil microbial communities even in the short term (Lazcano et al. 2013; Li et al. 2020). However, how inorganic fertiliser and biochar regulate soil microbial communities depends on fertiliser and biochar characteristics such as feedstock, pH, and application rate, as well as on soil properties such as pH, dissolved organic C, and C:N ratio (Bebber and Richards 2022; Li et al. 2020; Palansooriya et al. 2019; Wong et al. 2019). It is important to assess whether novel BMCs, where biochar has been micronised, could affect soil microbial diversity and composition in the short term.

Developing BMCs into novel liquefied forms is highly innovative and can address a continued gap within the sustainable fertiliser industry (Omidvar et al. 2025, 2026; Dissanayake et al. 2026). Economically viable, novel BMCs should thus be developed to facilitate adoption by farmers, especially if these novel formulations allow fertiliser co-application to be eliminated because co-fertilisation or fertiliser top-dressing imply additional labour and costs. This study specifically aimed to elucidate the mechanisms regulating nutrient cycling in pastures where various forms of BMCs were applied with and without co-fertilisation, and to explore the extent to which plant yield and profitability would increase while decreasing farm footprint. It was hypothesised that (1) nutrient-rich liquids that have colloidal biochar contained in suspension would differentially affect plant nutrient uptake leading to increased yield (Joseph and Taylor 2024; Joseph et al. 2021); (2) highly enriched BMCs would not require additional co-fertilisation and therefore increase economic viability (Joseph and Taylor 2024; Joseph et al. 2021); and (3) BMCs would not affect soil microbial composition in the short term because BMCs are designed to be applied at low rates (<1 t ha^{-1}) to make them economically viable (Farrar et al. 2022; Joseph et al. 2013, 2017). Understanding how different BMCs could modulate soil-microbe-plant systems would help design more efficient formulations and facilitate the adoption of emerging biochar-based fertilisers for a wide range of crops.

2 Material and methods

2.1 Site description

The experimental site is a pastureland cropping area located near Berrigan, New South Wales (NSW) (S35.677594 E145.804731. 35° 67′ S 145° 80′ E). Soil at the site is classified as Brown Chromosol and is a red-brown duplex soil with a sandy-loam texture (Isbell 2016). The Berrigan region experiences hot summers and cold winters with average daytime temperatures ranging from 13.1 °C to 31.0 °C and overnight temperatures from 4.0 °C to 17.0 °C; annual average rainfall is 438 mm (BOM 2024). For ten years prior to commencement of this experiment, the site has grown pasture crops using a mixture Italian ryegrass (*Lolium multiflorum*) and three clover varieties, Balansa clover (*Trifolium michelianum*), Crimson clover (*Trifolium incarnatum*), and Berseem clover (*Trifolium alexandrinum*) at a rate of 18:4:4:4 kg ha^{-1}, respectively. The pasture was fertilised for seven years prior to our experiment using a conventional fertiliser regime that included application of di-ammonium phosphate (DAP). The site was fenced to exclude animal grazing during and for three months prior to the experiment. In May 2023, three days before establishment and application of treatments, the entire site including buffer zones and unused areas was sown with the mixture pasture crop (Omidvar et al. 2025, 2026).

2.2 Treatments and experimental design

In this study, four different forms of BMC were developed and applied: (1) "BMC1" was produced from a wood-based feedstock at 600 °C in a commercial biochar kiln, micronised at ≤ 50 μm particle size and liquefied by blending with hot water; (2) "BMC2" was produced from the same feedstock as BMC1, micronised ≤ 50 μm particle size and liquefied using a water-based dispersion agent; 3) "BMC3" was produced from a wheat straw and poultry litter feedstock that was combined with minerals, basalt, diatomite, rock phosphate, bentonite, kaolinite, and ferrous sulfate ($FeSO_4$) in a ratio of 35:35:10:7:5:2.5:2.5:3 (dry w/w), respectively, pyrolyzed at 450 °C, micronised at ≤ 50 μm and liquefied using a P-enriched dispersion agent; and 4) "BMC4" was the same as the BMC3 but liquefied using hot water and enriched with a commercially available liquid fertiliser (Charlie Carp, NSW, Australia) (Supplementary Table 1). All pyrolysis conditions, feedstock specifics, and the nature of the dispersion agents used for liquefaction have been summarised in

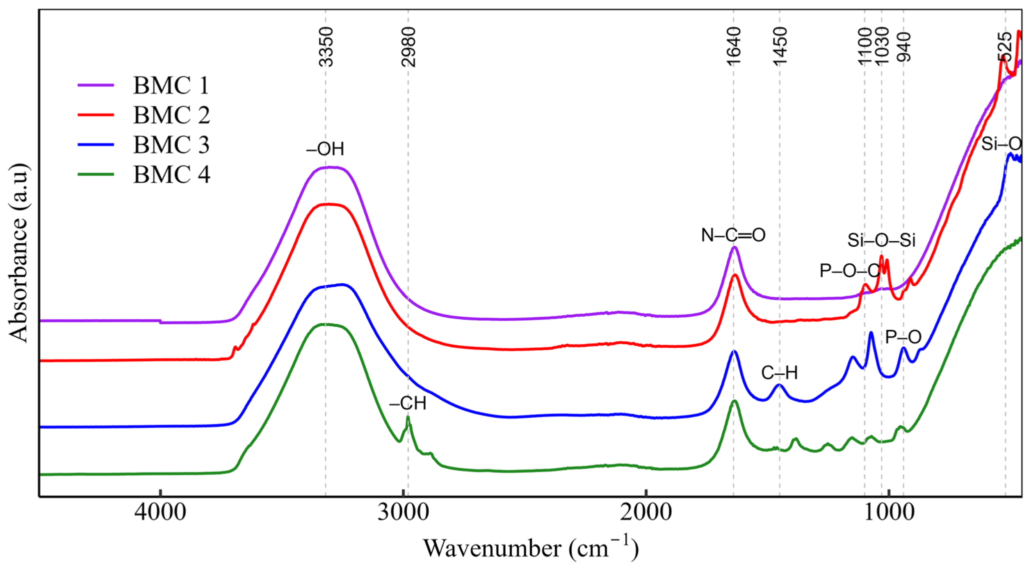

Fig. 1 Fourier transform infrared (FTIR) absorbance spectrum of biochar mineral complex (BMC) used in the study

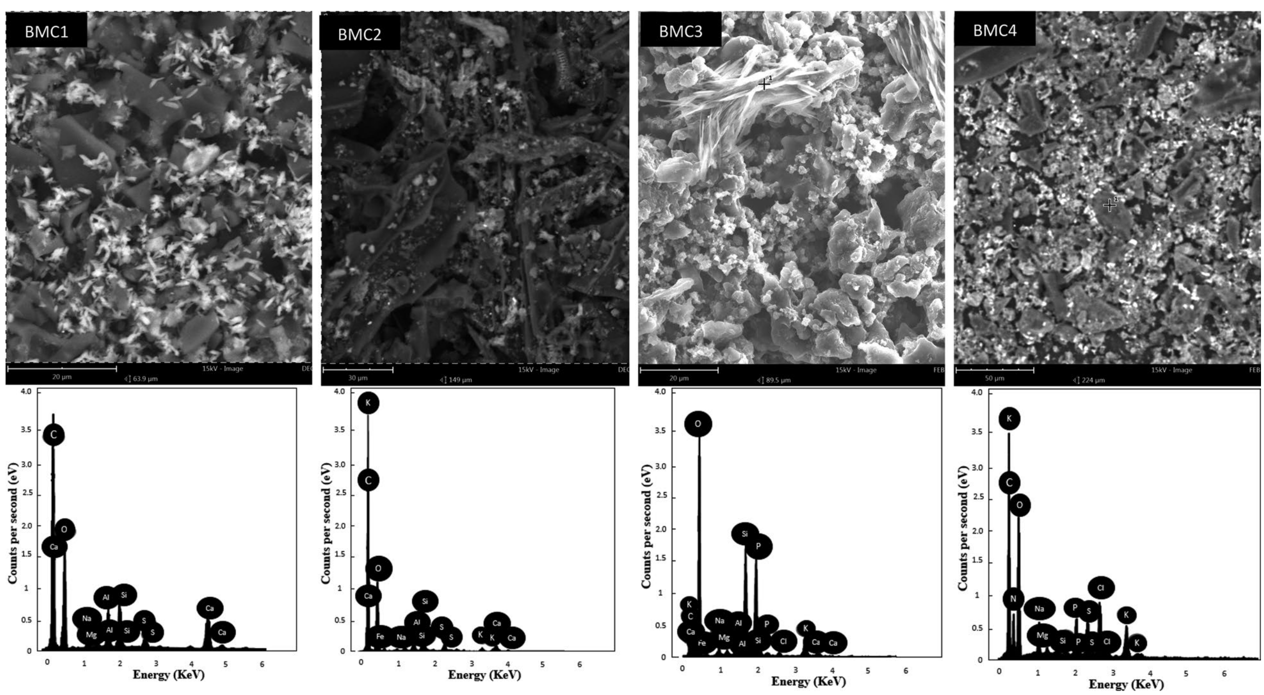

Fig. 2 Scanning electron microscopy (SEM) of biochar mineral complex (BMC) used in the study

Supplementary Table 1. All forms of liquefied BMC were characterised with Fourier transform infrared (FTIR) spectroscopy using the wavenumber range (450–4000 cm^{-1}) with a 16 cm^{-1} spectral resolution and 64 accumulations for each collection by the array (Perkin Elmers) (Fig. 1). All forms of liquefied BMC were characterised by scanning electron microscope (SEM) analyser (NanoSEM 350 FEI Netherlands) equipped with a Bruker X-ray energy dispersive spectroscope (EDS) (Fig. 2). The chemical composition of soil and different forms of BMC have been summarised in Table 1.

Table 1 Characterisation data for the soil and different forms of liquefied biochar mineral complex (BMC) used in the field trial

	Soil	BMC1	BMC2	BMC3	BMC4
EC (mS cm^{-1})	6.28	8.72	7.17	283	3.95
pH$_{H2O}$	6.18	3.57	6.04	3.28	7.62
Total C (%)	1.45	51.06	56.06	12.09	34.05
Total N (%)	0.13	1.13	1.01	0.96	1.84
C:N ratio	11.15	45.20	55.50	12.60	18.50
δ^{13}C (‰)	− 26.66	− 26.89	− 27.08	− 25.88	-27.36
δ^{15}N (‰)	5.21	3.17	2.40	− 2.75	10.95
P (mg 100 gr^{-1})	361.00	8.21	76.26	4719.05	13.1
K (mg 100 gr^{-1})	3710.00	36.91	84.38	1037.50	45.2
Al (mg 100 gr^{-1})	24,087.00	79.51	692.46	349.79	15.6
As (mg 100 gr^{-1})	21.00	ND	ND	ND	ND
B (mg 100 gr^{-1})	62.00	3.22	6.54	4.57	0.4
Ca (mg 100 gr^{-1})	1655.00	82.82	845.35	121.56	32.4
Cd (mg 100 gr^{-1})	1.00	ND	ND	ND	ND
Cr (mg 100 gr^{-1})	ND	0.60	4.10	0.83	0.1
Cu (mg 100 gr^{-1})	7.00	1.17	2.42	1.04	0.1
Co (mg 100 gr^{-1})	ND	0.02	0.18	0.16	ND
Fe (mg 100 gr^{-1})	12,084.00	94.64	478.36	501.99	15.2
Hg (mg 100 gr^{-1})	ND	ND	ND	ND	ND
Mg (mg 100 gr^{-1})	1225.00	24.74	113.65	95.78	9.6
Mn (mg 100 gr^{-1})	451.00	1.56	13.26	8.15	0.4
Mo (mg 100 gr^{-1})	ND	0.04	0.15	0.11	ND
Na (mg 100 gr^{-1})	135.00	16.08	151.43	246.94	17.6
Pb (mg 100 gr^{-1})	ND	0.36	3.17	0.16	ND
S (mg 100 gr^{-1})	207.00	60.58	528.53	221.61	19.1
Se (mg 100 gr^{-1})	ND	ND	ND	ND	ND
Si (mg 100 gr^{-1})	72.00	1.42	1.17	29.10	1.9
Zn (mg 100 gr^{-1})	26.00	1.53	5.46	3.53	0.2

EC: Electrical conductance; TC: total carbon concentration; TN: total nitrogen concentration; δ^{13}C: C isotopic composition; δ^{15}N: N isotopic composition; P: phosphorus; K: potassium; Al: aluminium; As: arsenic; B: boron; Ca: calcium; Cd: cadmium; Cr: chromium; Cu: copper; Co: cobalt; Fe: iron; Hg: mercury; Mg: magnesium; Mn: manganese; Mo: molybdenum; Na: sodium; Pb: lead; S: sulphur; Se: selenium; Si: silicon; Zn: zinc; ND: Not detected

The field trial was a randomised complete block design with six replicates and ten treatments. In total, 60 plots with an area of 5 m × 5 m were marked and plots were separated by 3 m buffer zones on each boundary (Fig. 3). Each form of liquefied BMC was applied at 200 kg ha^{-1} (dry weight BMC) using a modified applicator (Joseph and Taylor 2024). The BMC application rate has been based on the guidance provided to farmers in Joseph and Taylor (2024). Each block had forms of BMC and control with and without co-fertilisation of DAP and urea. Urea is the most commonly applied N source worldwide and is usually applied with P and K fertiliser sources (Skorupka and Nosalewicz 2021; Sande et al. 2024). Application of urea and DAP was a standard farmer practice (DPI 2021). The total N applied in inorganic farmer practice was at 64 kg N ha^{-1} and co-fertilisation was adjusted for BMC treatments to maintain the same N application rate, except BMC4 which was enriched with four times more at the rate of 270 kg N ha^{-1}.

2.3 Soil sample collection and chemical analysis

Soil samples were first collected immediately following site establishment and initial treatment application (week 0). Soil samples were collected again during the mid-late growing season in August 2023 (week 16) and at the same time as the first pasture harvest. All soil samples were taken from the surface layer (0–10 cm) and homogenized. A subsample of soil was immediately frozen for microbial analysis and the remaining sub-samples were air dried and passed through a 2-mm mesh sieve prior to analysis of nutrient concentrations. A subsample of air-dried soil (≈20 mg) was transferred into 8 mm × 5 mm tin capsules to measure soil total carbon (total C), total nitrogen (total N), and C and N isotope composition (δ^{13}C and δ^{15}N, respectively) using an Isotope Ratio Mass Spectrometer connected to a CN Eurovector Elemental Analyser (Ibell et al. 2013). Soil ammonium (NH_4^+–N) and nitrate (NO_3^-–N) concentrations were measured using 2 M KCl extraction method and analysed with a SmartChem 200 Discrete Chemistry Analyser (Unity Scientific, Brookfield, CT, USA) (Rayment and Lyons 2011). Nutrient concentrations including phosphorus (P), potassium (K), aluminium (Al), arsenic (As), boron (B), calcium (Ca), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), sodium (Na), lead (Pb), sulphur (S), silicon (Si), and zinc (Zn) concentrations were analysed using an ICP-OES Optima 5300 V, PerkinElmer, Waltham, MA, USA (Bai et al. 2017a, b).

2.4 Soil DNA extraction, sequencing, and bioinformatics analysis

To evaluate the effect of the different forms of BMC on soil microbial communities, DNA extractions were carried out in triplicate from the soil collected at week 16 using the DNeasy PowerSoil® DNA Isolation Kit (QIAGEN) following the company protocol. The extracted DNA samples were sent to GENEWIZ of Azenta Life Sciences company (Suzhou, China) for the preparation of amplicon sequencing libraries and Illumina sequencing. A MetaVx library preparation kit was used to construct the sequencing libraries. In brief, amplicons were generated using DNA between 20 and 50 ng to cover V3 and V4 hypervariable regions of 16S rRNA gene for bacteria and ITS rRNA gene for fungi. The forward and reverse primers were 338F (5′-CCTACGGRRBGCASCAGKVRVGAAT-3′) and 806R

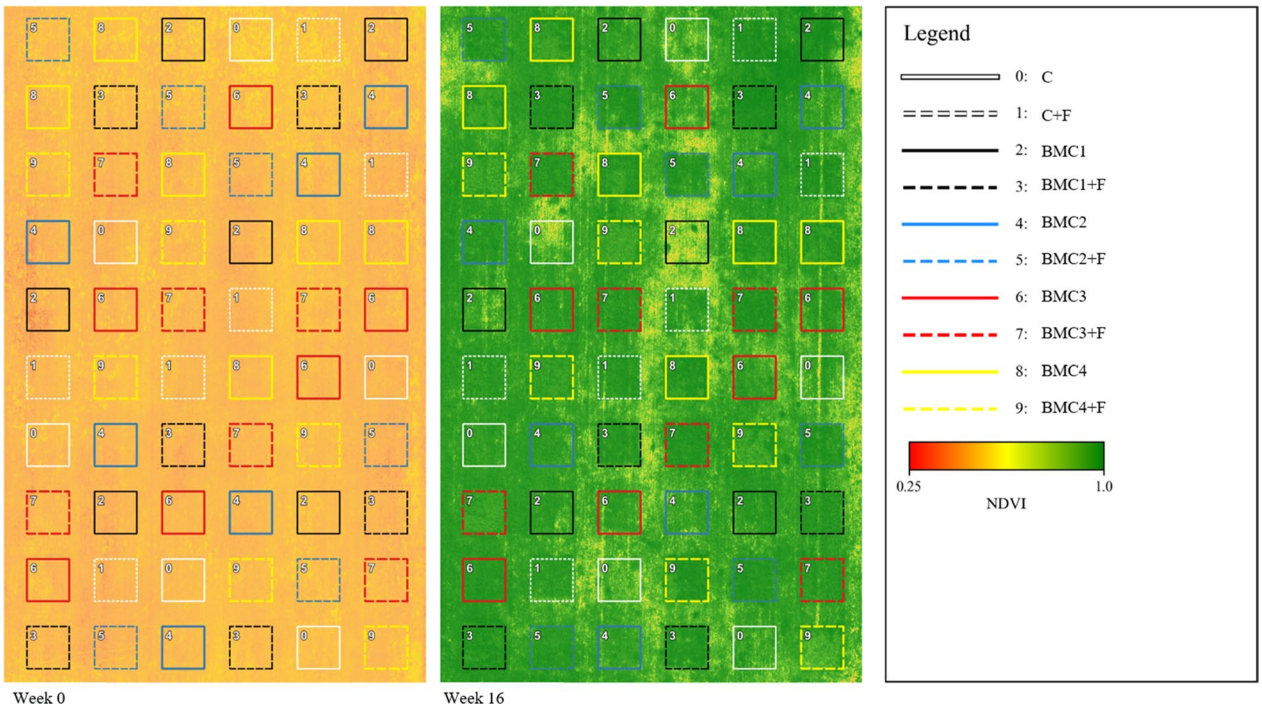

Fig. 3 Experimental site and treatments following 0 and16 weeks of application of four different forms of liquid biochar mineral complex (BMC) with and without inorganic fertiliser (F and NF, respectively), co-fertilisation compared with control (C) with and without inorganic fertilisation

(5′-GGACTACNVGGGTWTCTAATCC-3′)' for 16S rRNA and 'GTGAATCATCGARTC' and 'TCCTCC GCTTATTGAT' for ITS2 rRNA, respectively. Amplicon sequencing (paired-end, 2 × 300 bp) was conducted on an Illumina Novaseq Platform (Illumina, San Diego, USA) by GENEWIZ from Azenta Life Sciences.

Bioinformatic analyses were performed using FROGS 4.1.0. (Escudié et al. 2018; Bernard et al. 2021). Reads were merged with VSEARCH (2.17.0); unmerged reads, chimera, and low abundance sequences (< 0.005%) were discarded, and sequences corresponding to mitochondrial or chloroplastic RNA were removed. The remaining high-quality reads were grouped into amplicon sequence variants (ASVs). An additional step was used for fungal sequences, using the ITSx filter in FROGS to discard those sequences not assigned to the ITS region. Taxonomic affiliation was performed using the Silva 138 database for bacterial sequences and the UNITE 8.3 ITS database for fungal sequences. Alpha diversity metrics (observed richness, Chao1, Shannon, and inverse Simpson indices) were computed on data normalised to the smallest sample size. An analysis of variance (ANOVA) was used to test for significant differences in alpha diversity metrics between treatments. Non-metric Multidimensional Scaling (NMDS) based on Bray–Curtis distances and a subsequent multivariate analysis of variance (MANOVA) were carried out to analyse community structure and test for significant differences between treatments, respectively. The FungalTraits database (Põlme et al. 2020) was used to assign functional categories to the fungal ASVs. All statistical analyses were considered significant at $P < 0.05$.

2.5 Grass sample collection and analysis

We harvested the pasture grass on two occasions at weeks 16 and 22, reported as total yield, just before conventional harvest times, following the establishment of the experimental site. To measure grass yield, height, chlorophyll concentration, and foliar nutrient concentration, a 1 m^2 quadrat (1 m × 1 m) was placed at the centre of each plot to represent the sampling area. Chlorophyll concentration of the grass was measured using a Soil Plant Analysis Diagnostic (SPAD) index, determined by chlorophyll meter (atLEAF CHL PLUS, USA) and the height of grass was measured at the same sampling points as chlorophyll concentration using a measuring tape prior to grass harvest at week 16. The total grass yield within each quadrat was manually harvested using a grass shearer. Following harvest, the fresh weight of the grass collected from each quadrat was weighed using a digital balance (Salter Heston Blumenthal Precision Dual Platform Digital Kitchen Scale, UK) and yield data were calculated and reported as t ha^{-1}.

Pastures are usually planted with different ratio of multiple species, and a composite sample is commonly used to assess fodder nutrient concentrations (Serrano et al. 2024; Bozhanska et al. 2023; Moir et al. 2007). A sub-sample of fresh grass (100 g) was weighed to determine moisture concentrations by drying at 60 °C for at least 48 h to reach a constant weight, which then used to estimate dry biomass (Omidvar et al. 2025, 2026). Dried grass samples were finely ground using a Rocklabs™ ring grinder to measure total C, total N, $\delta^{13}C$, $\delta^{15}N$, and nutrient concentrations (Omidvar et al. 2025, 2026). The Al, As, B, Ca, Cr, Co, Cu, Fe, K, Mg, Mn, Na, P, Pb, S, Si, and Zn concentrations of grass samples were analysed using an ICP-OES (Optima-5300 V, PerkinElmer, Waltham, MA, USA) at Griffith University (Bai et al. 2017a).

2.6 Nutrient uptake, balance and use efficiency

Total N and P uptake were estimated as the grass yield (kg ha^{-1}) and nutrient concentrations in grass using the Eq. 1 (Baptistella et al. 2020):

$$\text{Nutrient uptake (kg N or P ha}^{-1}) = \frac{\text{Grass dry biomass content}\left(\text{KgDMha}^{-1}\right) \times \text{nutrients (\%)}}{100} \quad (1)$$

Partial nutrient (N and P) balances were determined by calculating the differences between the nutrient inputs and outputs, representing the nutrient uptake over the trial period, using the Eq. 2 (Touhami et al. 2022).

$$\text{Partial nutrient balance}\left(\text{kg N or P ha}^{-1}\right) = \text{nutrient input} - \text{nutrient output} \quad (2)$$

The N and P use efficiency was calculated by comparing the differences in yield (kg ha^{-1}) between different treatments and no-fertilised area (C) to the amount of N and P applied in each treatment, using the Eq. 3 (Singh et al. 2021).

$$\text{Nutrient use efficiency} = \frac{\text{Pastureyield}_T - \text{Pasture yield}_C}{\text{Applied N and P}} \quad (3)$$

2.7 Economic estimation

The input costs were estimated as the sum of all expenditure incurred for applying each treatment including BMC production, chemical fertilisers (DAP and urea) used in co-applications, labour for production and application, and freight from a 100 km radius of the experimental site (USD ha^{-1}); using Eq. 4:

$$\text{Input costs}\left(\text{USDha}^{-1}\right) = \sum \text{Costs}_{1,2,3\ldots n} \quad (4)$$

where Costs $_{1,2,\ 3..}$represents cost of each itemised cost specified above (Yang et al. 2020).

Cost to produce the BMC was estimated at US \$217 ha^{-1} including the sales price of liquefied BMC of USD 700 t^{-1} based on ex-factory available retail (Omidvar et al. 2025), with a freight cost of USD 300 t (based on current rates) and application cost of USD 17 ha^{-1} (Omidvar et al. 2025). The cost of DAP and UREA applications was at USD 40 and USD 44 t, respectively, based on the application rate of 100 kg ha^{-1} (Supplementary Table 2).

The gross return was estimated as the return by yield (kg ha^{-1}) under different treatments and estimated sale price (ESP) of pasture grass for the time of year obtained from farmer (USD ha^{-1}) using the Eq. 5 (Yang et al. 2020).

$$\text{Gross return} = \text{Yield}\left(\text{Kgha}^{-1}\right) \times \text{Sale price(ESP)(USDha}^{-1}) \quad (5)$$

The net return was estimated as the differences in gross return and input costs, using the Eq. 6 (Yang et al. 2020).

$$\text{Net return} = \text{Gross return-Input costs} \quad (6)$$

Revenue increase was calculated as the differences in yield between different BMC forms and non-fertilised area, multiplied by the sale price of the grass, using the Eq. 7 (Imran et al. 2023):

$$\text{Revenue increase(USDkg}^{-1}) = (\text{Yield}_{\text{BMCforms}} - \text{Yield}_{\text{Control}}) \times \text{Saleprice(USDha}^{-1}) \quad (7)$$

The cost was divided into fixed and variables to determine the break-even of BMC. The break-even of BMC was calculated where the sum of total costs equalled the increase in revenue from the additional yield generated in different BMCs using the Eq. 8 (Horváth 2017):

$$\text{Total revenues increase} = \text{Total cost of production} \quad (8)$$

This marks the point at which the costs are fully covered, and no profit or loss is incurred.

Benefit-cost ratio is an economic indicator which quantifies the financial return on investment (Patel et al. 2024). The benefit–cost ratio was calculated for each treatment using the Eq. 9 (Hassan et al. 2021).

Table 2 Soil pH, total carbon (Total C), total nitrogen (Total N), NH_4^+–N, NO_3^-–N, N isotope composition (δ ^{15}N) and total phosphorus (Total P) in response to four different forms of liquified biochar mineral complex (BMC) with and without inorganic fertiliser (F and NF, respectively), co-fertilisation compared with control (C) with and without inorganic fertilisation at weeks 0 and 16 following the treatment applications

	Time (week)	C				BMC1				BMC2				BMC3				BMC4			
		NF		F		NF		F		NF		F		NF		F		NF		F	
pH	16	5.81	±0.04A	5.79	±0.08A	5.92	±0.05A	5.74	±0.01A	5.93	±0.01A	5.78	±0.06A	5.82	±0.09AB	5.63	±0.11AB	5.63	±0.03B	5.56	±0.07B
Moisture (%)	16	15.42	±0.59	15.10	±0.65	15.82	±1.27	14.88	±1.07	15.62	±0.88	14.37	±1.45	15.65	±0.91	13.88	±1.08	14.66	±1.82	18.36	±3.17
Total C (%)	0	1.44	±0.04	1.54	±0.10	1.58	±0.16	1.52	±0.05	1.58	±0.04	1.61	±0.08	1.50	±0.03	1.57	±0.10	1.54	±0.04	1.69	±0.08
	16	1.59	±0.06	1.68	±0.07	1.68	±0.11	1.61	±0.10	1.66	±0.07	1.59	±0.04	1.77	±0.06	1.56	±0.09	**1.88**	**±0.18**	**1.61**	**±0.06**
Total N (%)	0	0.13	±0.00B	0.13	±0.01B	0.14	±0.02B	0.13	±0.00B	0.14	±0.00B	0.13	±0.00B	0.13	±0.00B	0.14	±0.01B	0.16	±0.01A	0.17	±0.01A
	16	0.14	±0.01	0.14	±0.01	0.14	±0.01	0.14	±0.01	0.14	±0.01	0.14	±0.01	0.15	±0.01	0.14	±0.01	0.16	±0.01	0.14	±0.00
NH_4^+–N (µg g^{-1})	0	5.22	±1.34B	8.06	±1.87B	4.92	±0.52B	5.26	±1.78B	7.30	±1.43B	5.96	±2.02B	5.88	±2.54B	5.73	±1.42B	**143.98**	**±67.82A**	**237.98**	**±39.41A**
	16	59.81	±37.76	40.80	±23.98	64.73	±29.61	50.16	±35.80	41.66	±22.74	67.26	±27.81	60.37	±26.77	60.13	±26.42	74.55	±55.06	83.62	±38.78
NO_3^-–N (µg g^{-1})	0	16.54	±3.08B	12.53	±3.95B	16.24	±3.27B	14.88	±0.23B	20.55	±6.13B	15.19	±2.19B	20.49	±5.15B	23.53	±6.16B	77.78	±24.44A	61.60	±19.17A
	16	13.19	±1.64B	8.81	±2.15B	11.80	±1.28B	11.91	±1.69B	17.90	±3.53AB	11.80	±1.46AB	12.38	±3.17B	10.11	±1.72B	**15.52**	**±1.96A**	**23.06**	**±4.34A**
δ ^{15}N (‰)	0	5.21	±0.28	5.26	±0.41	4.91	±0.13	5.17	±0.14	4.78	±0.18	4.59	±0.37	5.16	±0.36	5.37	±0.19	5.76	±0.31	4.99	±0.31
	16	6.74	±0.52	6.58	±0.28	6.58	±0.34	6.51	±0.53	6.08	±0.35	6.36	±0.39	6.06	±0.38	6.29	±0.12	**7.14**	**±0.37**	**6.05**	**±0.17**
Total P (mg 100 g^{-1})	0	19.16	±6.88	16.99	±7.44	13.00	±5.42	21.49	±5.47	22.54	±4.39	18.48	±6.23	16.02	±5.53	19.40	±5.21	22.58	±7.27	30.27	±14.19
	16	33.86	±2.30	29.52	±3.82	33.12	±2.00	32.74	±4.20	33.53	±1.51	35.02	±4.08	33.65	±1.46	46.37	±11.27	31.45	±2.83	32.53	±1.89

Values shown are mean ± SE (n = 5)

Different uppercase letters in a row indicate significant main effects for different forms of BMC and paired values in bold font indicate significant fertiliser effect (F *vs.* NF) at ($P < 0.05$)

$$\text{Benefit-cost ratio} = \frac{\text{Gross income}(\$\text{ha}^{-1})}{\text{Total cost of production}(\$\text{ha}^{-1})} \quad (9)$$

Benefit-cost ratio greater than 1.0 would indicate the benefits outweigh the costs, suggesting that the investment is viable (Patel et al. 2024).

All calculations were computed by converting Australian dollar (AUD) to United States dollar (USD) using 1 USD = 1.45 AUD conversion rate as of October 2024.

2.8 Statistical analysis

The data were tested for normality and homogeneity of variances to ensure that the assumptions required for analysis of variance (ANOVA) were met. Three-way ANOVA followed by HSD Tukey test were used to detect the main effects of sampling time, forms of BMC, co-fertilisation, and their interactions on soil. Two-way ANOVA and HSD Tukey test were used to determine the main effects of forms of BMC, co-fertilisation, and their interactions on grass properties and soil moisture. One-way ANOVA was used to detect differences among treatments in the N and P use efficiencies. ANOVAs were also performed on the fungal functional categories to determine potential differences in the relative abundance of (a) saprotrophs and (b) plant pathogens among treatments. The means were compared using Tukey's test at the 0.05 probability level. Principal component analysis (PCA) of the data was performed to determine the interactions between soil and grass chemical and microbial variables and yield using GraphPad Prism 10.4.0.

3 Results

3.1 Changes in soil pH, moisture concentration, and chemical properties

Soil pH was significantly lower in BMC4 compared with all other treatments except with BMC3 (Table 2). Soil moisture and total C concentrations were not affected by the applied treatments (Table 2). Soil total C was not affected by any treatments (Table 2). Soil total N, NH_4^+–N and NO_3^-–N concentrations were significantly higher in BMC4 compared with all other treatments at week 0, although no differences were found among treatments for soil total N and NH_4^+–N at week 16 (Table 2). Similarly, the applied treatments did not affect soil δ^{15}N values, although a significant increase of soil δ^{15}N values was found between weeks 0 and 16 in BMC4 (Table 2). Soil P concentrations were not affected by any forms of BMC nor by co-fertilisation (Table 2). Similarly, treatments did not affect the concentrations of soil K, Al, Ca, Fe, Mg, Mn, Na, S, and Zn (Supplementary Tables 3 and 4).

3.2 Effects of different forms of BMC and co-fertilisation on soil microbial communities

A total of 429,810 16S rDNA quality-filtered reads were retrieved, which were clustered into 615 bacterial

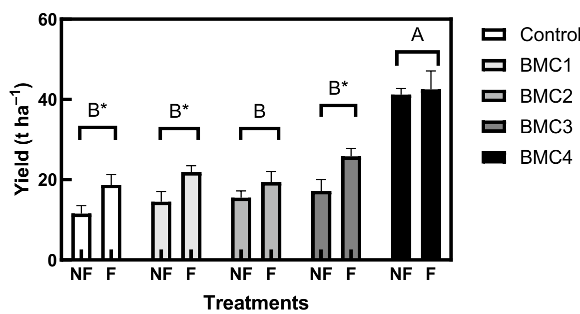

Fig. 5 Total pasture yield in response to four different forms of liquid biochar mineral complex (BMC) with and without inorganic fertiliser (F and NF, respectively), co-fertilisation compared with control (C) with and without inorganic fertilisation. Values shown are mean ± SE (n = 6). Different uppercase letters represent significant differences in BMCs, and asterisks represent significant differences in co-fertilisation (NF vs F) using Tukey's post hoc test following two-way ANOVA at $P < 0.05$

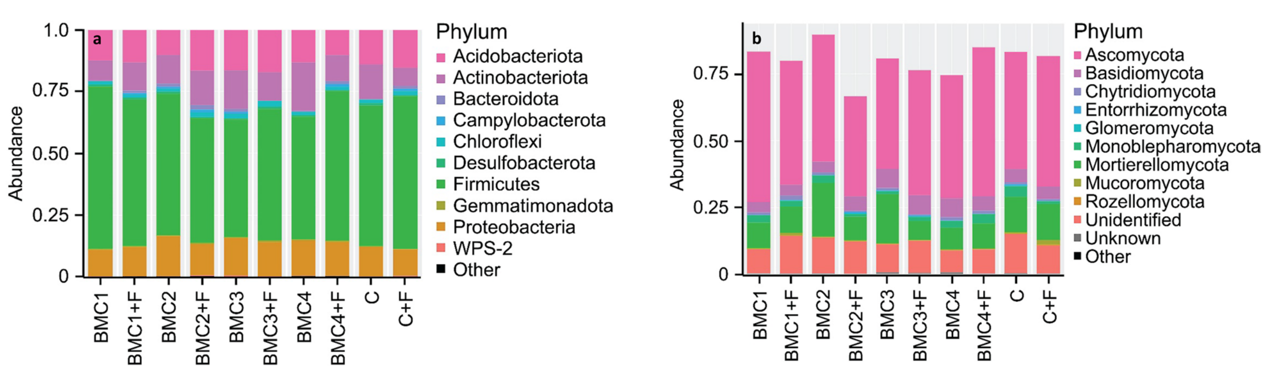

Fig. 4 **a** Bacterial and **b** fungal community composition (relative abundance) at the phylum level following 16 weeks of application of four different forms of liquid biochar mineral complex (BMC) with and without inorganic fertiliser (F and NF, respectively), co-fertilisation compared with control (C) with and without inorganic fertilisation

Table 3 Grass chlorophyll concentration, total carbon (Total C), total nitrogen (Total N), N isotopic composition ($\delta^{15}N$), and total phosphorus (Total P) in response to four different forms of liquefied biochar mineral complex (BMC) with and without inorganic fertiliser (F and NF, respectively) co-fertilisation compared with control (C) with and without inorganic fertilisation

	C				BMC1				BMC2				BMC3				BMC4			
	NF		F		NF		F		NF		F		NF		F		NF		F	
Chlorophyll (mg g^{-1})	40.90	±2.60	46.26	±2.11	41.00	±3.20	45.78	±1.53	42.37	±2.06	45.33	±0.89	41.40	±2.12	42.10	±2.05	43.35	±1.65	47.46	±1.00
Total C (%)	39.82	±1.79	38.20	±0.64	39.24	±3.05	40.64	±0.90	41.34	±1.33	40.96	±1.43	40.24	±1.65	39.38	±1.32	41.54	±0.58	38.54	±1.80
Total N (%)	2.30	±0.16B	2.22	±0.10B	2.16	±0.12B	2.26	±0.10B	2.30	±0.14AB	2.84	±0.51AB	2.32	±0.16B	2.40	±0.17B	3.18	±0.25A	3.00	±0.29A
$\delta^{15}N$ (‰)	2.07	±0.57B	1.48	±0.25B	1.13	±0.43B	0.60	±0.26B	0.59	±0.48B	2.02	±1.18B	1.56	±0.58B	1.07	±0.55B	6.57	±0.74A	5.35	±1.41A
Total P (mg 100 g^{-1})	256.15	±35.85	289.49	±37.20	274.28	±32.14	301.65	±34.06	251.82	±28.08	324.39	±47.29	321.33	±38.83	364.29	±53.19	328.88	±35.24	376.03	±8.56

Values shown are mean ± SE (n = 5). Different uppercase letters in a row indicate significant main effects for different forms of BMC and paired values in bold indicate significant fertiliser effects (F vs NF) for each treatment at ($P < 0.05$)

Table 4 Grass nitrogen (N) and phosphorus (P) uptake and balance in response to four different forms of liquefied biochar mineral complex (BMC) with and without inorganic fertiliser (F and NF, respectively) co-fertilisation compared with control (C) with and without inorganic fertilisation

	C				BMC1				BMC2				BMC3				BMC4			
	NF		F		NF		F		NF		F		NF		F		NF		F	
N uptake (kg ha^{-1})	**50.10**	**±11.09B**	**78.83**	**±13.58B**	**65.12**	**±12.75B**	**98.91**	**±10.37B**	**68.01**	**±10.40B**	**97.60**	**±21.51B**	**81.07**	**±21.90B**	**123.14**	**±13.85B**	**259.61**	**±15.69A**	**254.33**	**±45.37A**
N balance	− 50.01	±11.10B	− 14.84	±13.59B	-62.62	±12.76B	− 34.92	±10.37B	− 65.52	±10.40B	− 33.61	±21.51B	− 75.07	±21.91B	− 55.64	±13.86B	**5.98**	**±15.69A**	**72.77**	**±45.38A**
P uptake (kg ha^{-1})	5.24	±1.33C	9.79	±1.84C	7.90	±1.58BC	13.23	±2.05BC	7.51	±1.31BC	11.20	±2.11BC	**11.10**	**±3.20B**	**19.05**	**±3.62B**	26.82	±2.49A	31.62	±4.45A
P balance	**− 5.25**	**±1.33B**	**10.21**	**±1.85B**	**− 7.70**	**±1.58B**	**2.97**	**±2.06B**	**-7.31**	**±1.31B**	**4.99**	**±2.11B**	**− 5.40**	**±3.21B**	**2.65**	**±3.62B**	**12.17**	**±2.49A**	**23.37**	**±4.46A**

Values shown are mean ± SE (n = 5). Different uppercase letters in a row indicate significant main effects for different forms of BMC and paired values in bold font indicate significant fertiliser effect (F vs. NF) at ($P < 0.05$)

ASVs. The most dominant bacterial phyla were Firmicutes (56.27%), Acidobacteria (13.96%), Proteobacteria (13.03%) and Actinobacteria (12.14%), which together accounted for 95.40% of the total number of bacterial reads (Fig. 4a). A total of 2,155,825 ITS rDNA high-quality fungal reads were obtained and clustered into 677 fungal ASVs. The most dominant fungal phyla were Ascomycota (47.06%), Mortierellomycota (11.68%), Basidiomycota (5.33%), accounting for 64.07% of the fungal sequences. A relatively large proportion of fungal reads remained unclassified (31.54%) (Fig. 4b). Rarefactions curves are provided in Supplementary Fig. 2. No significant differences were observed in bacterial and fungal alpha diversity metrics among the treatments (Supplementary Fig. 3 and 4). Similarly, no differences were detected in terms of bacterial and fungal community structure between treatments, as evidenced by the NMDS and MANOVA (Supplementary Fig. 4). In all treatments, the most abundant fungal functional categories based on the FungalTraits database were the saprotrophs and plant pathogens (Supplementary Fig. 5). Applying different forms of BMCs did not influence the relative abundance of these two ecological guilds.

3.3 Changes in grass yield and quality

Total pasture yield was higher in BMC4 compared with all other treatments (Fig. 5). Co-fertilised BMC1 and BMC3 had significantly higher yield compared with the un-fertilised BMC1 and BMC3 (Fig. 5). Pasture in the BMC4 plot had significantly higher grass height compared with the other treatments (Supplementary Table 5). Higher grass height was also observed in the co-fertilised BMC1, BMC3 and control compared with that of these treatments without co-fertilisation (Supplementary Table 5).

Foliar chlorophyll concentration was not affected by treatments, but co-fertilisation increased chlorophyll concentration compared with those without co-fertilisation (Table 3). In particular, grass harvested from plots amended with BMC4 had significantly higher TN concentrations compared with the control, BMC1, and BMC3 plots (Table 3). Grass TN concentration was higher in BMC4 compared with the control, BMC1 and BMC3 plots (Table 3). BMC4 had significantly higher $\delta^{15}N$ values compared with all other treatments (Table 3). Co-fertilisation did not significantly alter grass total C, TN nor $\delta^{15}N$ values (Table 3). Grass in the BMC4 had higher K concentration compared with other forms of BMC and the control, and higher Na concentration than grass from the BMC1 and BMC2 plots (Supplementary Table 5). No interactions between treatments and co-fertilisation were observed for any grass nutrient concentrations (Supplementary Table 6).

BMC4 had significantly higher N balance, N uptake, and NUE than other treatments (Table 4, Fig. 6a). N balance was positive only in BMC4 and co-fertilisation further increased N balances in BMC4 (Table 4). BMC4 had significantly higher P balance and P uptake than other treatments (Table 4). Co-fertilised BMC4 had significantly higher PUE than other treatments (Fig. 6b). No differences in PUE were found between fertilised and co-fertilised BMC4 (Fig. 5b). Soil and plant variables were separated in BMC4 from all other treatments (Fig. 7). The first two principal components (PC1 and PC2) of PCA explained 29.27% and 46.60% of the variance, respectively, accounting for a cumulative 75.87% of the total variation (Fig. 7).

3.4 Cost and benefit analyses

The highest net income was achieved with BMC4 followed by co-fertilised BMC4 > co-fertilised BMC3 > co-fertilised BMC1 > co-fertilised control > BMC3 > BMC1 > BMC2 > Control (Table 5). The break-even point for BMC ranged between USD 234 and USD 2,853, with the lowest for BMC2 and the highest for BMC4 (Table 5). The benefit-cost ratio ranged between 1.93 and 2.54 where co-fertilised BMC3 and BMC4 (with and without co-fertilisation) had higher benefit-cost ratios than fertilisation only (Table 5).

4 Discussion

4.1 Yield response to BMCs

Our hypothesis stating that highly enriched BMC does not require further co-fertilisation was confirmed. Applying BMC4 more than doubled yield compared with all other forms of BMCs and inorganic fertiliser and improved both N- and P-use efficiencies. Plants have two strategies to increase N- and P-use efficiency, either through: (1) an increased capacity to acquire N and P from the soil or, (2) by optimising N and P utilisation; both allowing plants to grow high yields under nutrient-limited scenarios (Neto et al. 2016). Biochar micronisation allows fast biochar movement within the soil profile, transporting nutrients with it and increasing water solubility of nutrients, all contributing to improved nutrient uptake in the rhizosphere (Wang et al. 2019; Lehmann and Joseph 2024). Biochar micronisation has previously shown to increase root biomass and P concentration of peas but did not directly lead to improved pea yield (Fišarová et al. 2024). In our current study, the process of producing liquefied colloidal biochar may have helped the applied biochar reach the root zone, facilitating N and P uptake. All BMCs contained micronised biochar with approximately 50 µm particle size. However, biochar with different surface areas can form different organo-mineral complexes on the surface, thus differentially

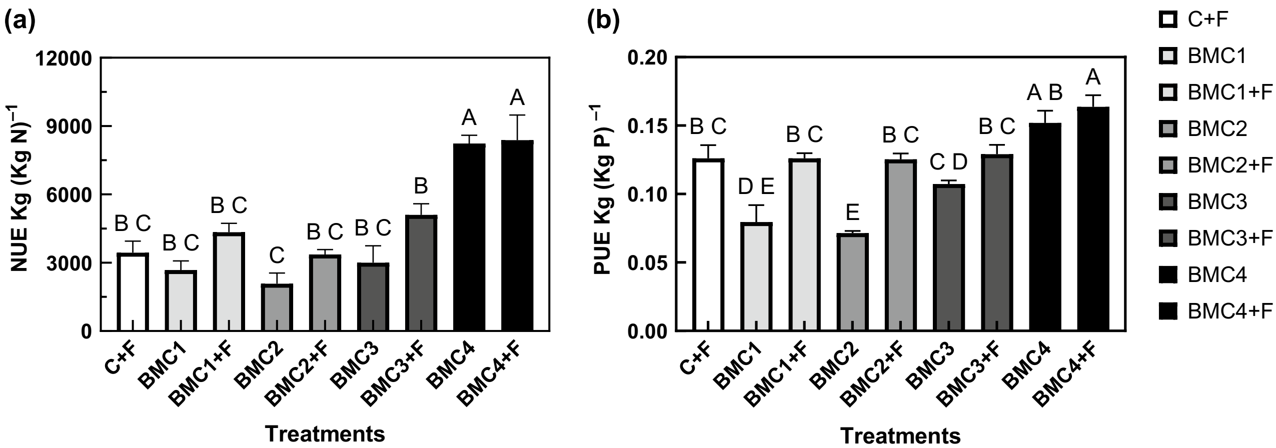

Fig. 6 Grass **a** nitrogen and **b** phosphorus use efficiency (NUE and PUE, respectively) in response to four different forms of liquid biochar mineral complex (BMC) with (+F) and without co-fertilisation, compared with the control with (C+F) and without (C) co-fertilisation. Values shown are mean ± SE (n = 5)

affecting nutrient cycling in the soil (Ma et al. 2016). Here, we also showed through SEM images that the surface and structure differed among the different forms of BMCs despite all being micronised, which may explain their different effects on nutrient cycling. We observed BMC4 had a distinct peak around 3000 cm^{-1} associated with –CH functional groups. High –CH functional groups suggest high organic concentration in a substrate (Lin et al. 2022). BMC4 was rich in organic matter and N concentration, which is supported by its low C:N ratio. We have used another form of BMC produced with a manure:straw feedstock, as was the case for BMC4, in a pot trial which has shown to significantly improve N retention through decreased N leaching (Dissanayake et al. 2026). Hence, a combination of increased N availability in root zone and improved N retention resulted in increased N assimilation, which could have partly contributed to increased yield in the BMC4 treatment compared with other BMCs.

BMC1-3 led to similar yield. Biochar type, production temperature, and C:N ratio are the three major factors influencing yield response to biochar application (Bai et al. 2022; Joseph et al. 2021). Usually, biochar produced with feedstock manure rather than wood, those produced under 500 °C, and those having C:N ratio less than 100 favor plant yield increases (Bai et al. 2022). BMC1-2 and BMC3 differed in feedstock types (wood *vs*. manure:straw, respectively) and production temperature (600 °C vs 450 °C, respectively) but all had C:N ratio under 100. BMC2 and BMC3 showed distinct higher peaks related to phosphate and phosphoryl functional groups at 1100 cm^{-1} than those of BMC1. Differences in phosphate and phosphoryl functional groups would drive P solubility and plant P assimilation (Chen et al. 2021; Xiong et al. 2023) suggesting BMC2 and BMC3 had the potential to further facilitate P assimilation and solubility due to higher phosphate and phosphoryl functional groups than those of BMC1. BMC2 had higher Si–O functional groups whereas BMC1 had higher negatively charged functional group of –OH than those of their BMC counterparts. BMC1 was also liquefied by hot water which promotes the oxidation of biochar surfaces, introducing functional groups such as OH and COOH. The Si–O functional groups are involved in increased P uptake in plants through releasing P in soil and/or

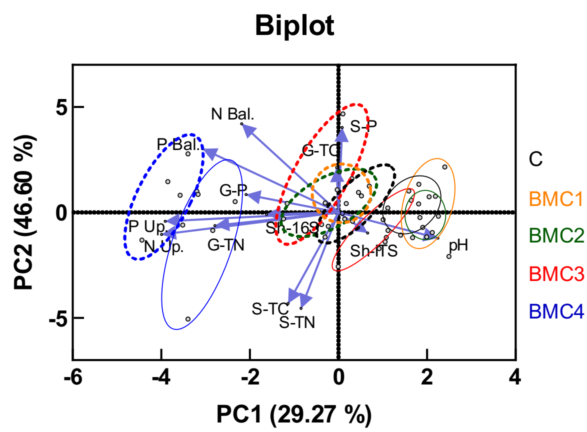

Fig. 7 Principal component analysis (PCA) of the soil and grass chemical and microbial diversity data following application of different forms of liquid biochar mineral complex (BMC) with co-fertilisation (dotted circles) and without co-fertilisation (solid circles) compared with the control. The biplot shows relationships between different treatments and variables measured in the study including soil (S) and grass (G), total nitrogen (TN), total carbon (TC), phosphorus (P), N and P balances (Bal) and uptakes (Up), and Shannon index (Sh) for bacteria (16S) and fungi (ITS).

Table 5 Cost and benefit analyses in response to four different forms of liquefied biochar mineral complex (BMC) with and without inorganic fertiliser (F and NF, respectively), co-fertilisation compared with control (C) with and without inorganic fertilisation

	C		BMC1		BMC2		BMC3		BMC4	
	NF	F	NF	F	NF	F	NF	F	NF	F
Gross income ($ ha^{-1})	853.68	2152.20	1397.97	2372.35	1334.50	1853.85	1785.57	2925.70	5382.20	5396.08
Total cost ($ ha^{-1})	451.95	985.60	710.40	1130.30	688.00	947.30	847.20	1325.60	2116.60	2197.60
Net Income ($ ha^{-1})	401.73	1306.6	687.57	1242.05	646.5	906.55	938.37	1600.1	3265.6	3198.58
Yield increase (t ha^{-1})	–	7.63	3.20	8.93	2.82	5.88	5.48	12.18	26.63	26.72
Net profit ($ ha^{-1})	–	687.22	135.22	689.63	94.12	354.17	385.98	1047.72	2713.22	2646.20
Break even BMC	–	–	275.18	829.63	234.11	494.16	525.98	1187.71	2853.21	2786.2
Benefit cost ratio	1.88	2.18	1.96	2.09	1.94	1.95	2.10	2.20	2.54	2.45

All variables are presented in USD. BMC production cost included at $700 t^{-1} and shipping cost at $300 t^{-1}. DAP and urea fertilisers included at $400 and $440 t^{-1}, respectively. Sale price was estimated at $170 t ha^{-1}

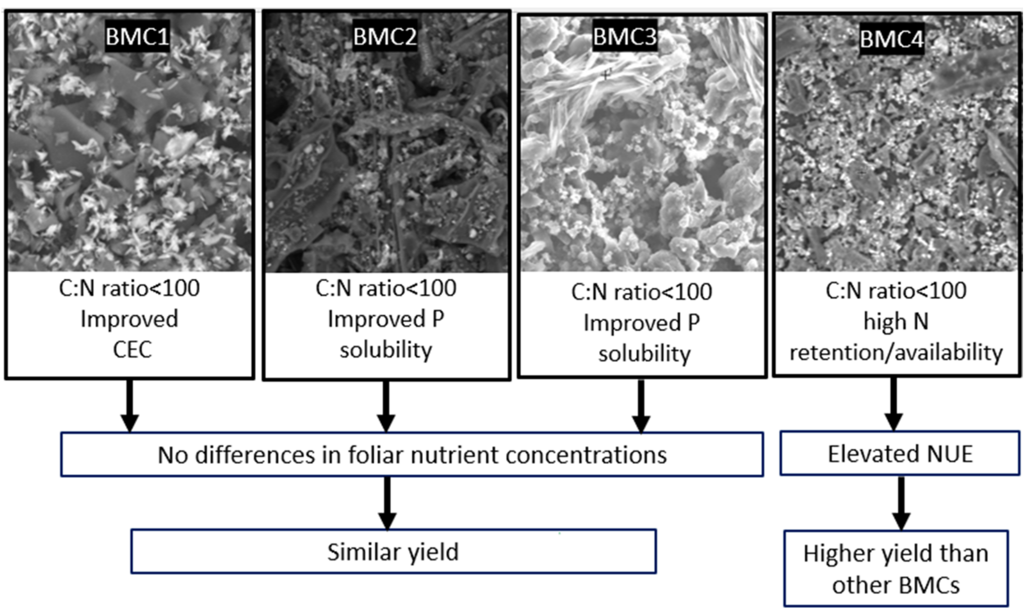

Fig. 8 Simplified schematic to showing biochar mineral complex (BMC) types affecting crop yield

stimulating root growth (Mückschel et al. 2025), and high frequency of negatively charged functional groups increases soil CEC and affects root nutrient uptake (Trubenbacher et al. 2025). The higher P assimilation and solubility exhibited by BMC2 and BMC3 than BMC1 was associated with liquefication method. Both BMC2 and BMC3 were liquefied using a P-enriched dispersion agent whereas BMC1 was liquefied using hot water. Biochar in the BMC1 treatment was wood-based, a feedstock that has shown to improve soil nutrient cycling for plant uptake through enhanced N retention and increased CEC (Adhikari et al. 2024; Nguyen et al. 2017a, b). Our study suggested that BMCs likely employed distinct mechanisms to supply nutrients such as N and P to plants while maintaining yield (Fig. 8).

Co-fertilised BMC1 and BMC3 plots had similar yield compared with that of inorganic fertilisers. Co-fertilised BMC1 and BMC3 treatments also had similar P use efficiency to inorganic fertilisation, despite the fact that BMC3 was P-enriched. Soil was both N and P limited, however, soil also had inherently high Al and Fe concentrations that contribute to increased P limitation at the study site. High Al and Fe concentrations lead to increased P immobilization, leaving P unavailable for plant uptake and assimilation (Zheng et al. 2024). Applying co-fertilisation improved P balances for BMC1 and BMC3 but soil remained N limited as shown by negative N balance. Both urea and DAP were used as co-fertilisers which contain N in readily available forms for plants to assimilate, and the ammonium in DAP formula increases

P availability by affecting P solubility and soil pH in the root zone (Chowdhury et al. 2020). In the current study, soil pH was not affected by co-fertilisation; however, co-fertilisation with DAP may have increased P solubility in addition to those being available from BMC1 and BMC3. Co-fertilised BMC1, BMC3, and inorganic fertiliser treatments all showed a positive P balance, but plants were still mining N from soil as evidenced by negative N balances. An increase in either N or P supply, where N and P limit growth, results in increased plant growth by allocating more resources towards the limiting element (Ågren et al. 2012). It is likely that co-fertilised BMC1, BMC3, and inorganic fertiliser treatments reduced P limitation, which led to increased yield by masking N limitation. Interestingly, soil N mining did not occur in BMC4 as evidenced by the positive N balances, despite the fact that pasture yield was doubled in BMC4. The minimum and maximum recommended N application rates for pasture crops are 100 and 400 kg N ha^{-1} yr^{-1} (DPI 2021). BMC4 was enriched with four times more N than the other BMCs and inorganic fertiliser, even though BMC4 was applied at a rate of 32% less than the maximum recommended. Insufficient N concentrations in the co-fertilised treatments may thus partly explain why yield in these treatments was not as high as that of BMC4. Our study clearly suggests that soil initial N and P limitations must be considered when BMCs are being applied to decide if co-fertilisation is required.

BMC4 provided higher quality fodder than other treatments as shown through higher foliar TN concentration than other treatments. Total N × 6.25 is used to calculate crude protein (Bai et al. 2017b). Crude protein is one of the major foliar nutrient concentrations to assess fodder quality and has shown to be affected by fertiliser types (Serrano et al. 2024; Bozhanska et al. 2023; Moir et al. 2007). BMC4 had higher NUE compared with other BMCs and, as a result, provided a higher quality fodder for livestock than other BMCs. BMC1-3 had similar fodder quality. Our finding is consistent with another study which shows some fodder nutrient concentrations such as calcium, magnesium, and K may not be necessarily affected by nutrient inputs (Moir et al. 2007). We also did not find any significant differences in majority of foliar nutrient concentrations, which supported lack of differences in fodder quality among BMC1-3.

4.2 Soil microbial response to BMCs

BMCs, inorganic fertiliser and co-fertilisation did not influence the bacterial and fungal alpha and beta diversity metrics at week 16 following treatment application. The fertiliser forms, their application in combination with other amendments and their application rates may affect soil microbial structure and composition (Li et al. 2020; Wang et al. 2021), with varying results. For example, biochar co-applied with chemical fertiliser was shown to improve microbial community structure, whereas biochar alone did not affect soil microbial communities (Li et al. 2020; Tian et al. 2016). In terms of N application rates, soil bacterial diversity has been reported to increase with increasing N application rate while an opposite trend has been reported for fungal diversity (Huang et al. 2023). Contrastingly, other reports have shown a decrease in soil microbial diversity induced by increased inorganic N fertilisation rates in the long term (Bebber and Richards 2022; Yang et al. 2022). A lack of effect of N fertilisation in terms of rates or fertiliser forms on microbial diversity metrics has been reported even though microbial functions have been affected by fertilisation (Tong et al. 2024). These contrasting results highlight the need to get a better understanding of the mechanisms underpinning BMC effects on the soil functioning and hence on microbial processes, beyond their sole impact on the composition of soil microbial communities. Such functional approaches have been implemented through the analysis of gene expression shifts following biochar application, showing a reduction in gene expression by pathogenic fungi in the rhizosphere of plants growing on biochar-amended soils and a concomitant enrichment of gene expression of beneficial soil microorganisms associated with plant growth (Hewitt et al. 2023). However, these positive functional shifts may be dependent on the biochar formulation and on site-specific soil and management conditions, which calls for further research.

Here, no differences were found among treatments in the relative abundance of fungal pathogens nor of fungal saprotrophs, which contrasts with results from Dai et al. (2018) and Hewitt et al (2023). The apparent lack of effect of BMC treatments here may be due to the relatively low N inputs of all tested BMC forms, except for the N-enriched BMC4. As previously reported, low and intermediate levels of N input may not affect soil bacterial communities (Fierer et al. 2012; Zeng et al. 2016). Other factors known to affect the diversity and composition of soil microbial communities are soil organic C and pH (Fierer and Jackson 2006; Sheng and Zhu 2018). In the current study, shifts in soil pH induced by the different forms of BMCs were probably not sufficient to affect soil microbial diversity and composition within 16 weeks, and no differences in soil TC were observed among treatments. Collectively, a combination of low nutrient application rates and low C inputs could be responsible for the lack of BMC effects on the soil microbial community in the short term. However, in the long term, it is expected that BMCs would increase soil C accumulation, which may induce detectable shifts in the soil microbial community and, in particular, in the proportion of saprotrophs.

4.3 Economic returns of BMCs

The application of BMC demonstrated a positive economic return, with net profit exceeding costs. The cost of biochar application can vary between \$150 t^{-1} and \$2100 t^{-1}, mainly driven by application expenses and government incentives, though most actual cost has been estimated at \$290 t^{-1} (Sorensen and Lamb 2018). In this study, the total cost of BMC, including shipping and spraying, was estimated to be up to \$217 t ha^{-1} with the break-even point varying between \$234 and 2853 ha^{-1} depending on the different forms of BMC applied. When the benefit-cost ratio is greater than 1, it indicates that benefits outweigh costs (Patel et al. 2024). In this study, the benefit-cost ratio ranged between 1.94 and 2.54, highlighting that an investment in BMC application is economically viable. Furthermore, additional revenue generated by increased pasture production compared with the control further emphasised economic feasibility of BMC technology helping to demonstrate its potential as a sustainable and profitable investment for farmers. It should be noted that applying co-fertilisation further increased revenue and that the cost of co-fertilisation was negligible compared with BMC and labour costs. Our short-term study indicated that BMCs are economically viable; however, the results should be interpreted with caution, as the economic return on value added biochar products can be complex. Trade-offs such as government incentives, nutrient co-application, environmental conditions such as drought spells, application frequency, transportation logistics, and source of biochar may influence profitability outcomes (Omidvar et al. 2026; Fang et al. 2021; Goldan et al. 2023; Karer et al. 2013; Kraut-Cohen et al. 2023; Pandit et al. 2018; Sorensen and Lamb 2018; Tisserant and Cherubini 2019). These considerations highlight the need for comprehensive, long-term benefit–cost analyses.

BMCs generally showed a potential to be economically viable in this study. Our complementary short-term studies have also shown a potential to decrease nutrient inputs without compromising yield, improving root nutrient intake and decreasing N leaching (Dissanayake et al. 2026; Omidvar et al. 2025; Trubenbacher et al. 2025). In a pot trial, one form of BMC reduced N and P inputs by 23% and 48%, respectively, compared with conventional organic fertilisers, without compromising crop yield (Dissanayake et al. 2026). BMCs are applied in low rates to increase adoptability in terms of cost. As a result, an annual removal of 75 kg CO_2e ha^{-1} at 200 kg ha^{-1} application rate of BMC is expected—a relatively small amount (Omidvar et al. 2025). However, long term application overtime should have implications on soil C accumulation and health through formation of organo-mineral complexes and C stabilisation in soil and biochar surfaces (Darby et al. 2016; Joseph et al. 2021). The liquefied BMCs has a further potential to be diluted and applied as foliar application which will be highly innovative (Joseph and Taylor 2024). The short-term implications of BMCs on crop yield and decreased environmental footprints are promising and long-term implications under various crops, climatic conditions and soil types are required to be assessed to facilitate BMC adoptions.

5 Conclusion

All forms of biochar mineral complex (BMC) showed an increase in yield compared with unfertilised control that was dependent on the BMC type. For example, the highly N enriched BMC4 doubled pasture yield due to improved N and P uptake and use efficiencies. Other BMCs either enriched by P or co-fertilised with urea and DAP also increased yield mainly because of improved P availability that masked inherent N limitation. The BMC enriched by N was the only formula that provided positive N balance, suggesting that plants did not mine N from existing soil reserves. Soil microbial composition and diversity were not affected by any forms of BMC. The N enriched BMC4 outperformed inorganic fertiliser application and did not require co-fertilisation, which meant for farmers to apply and forget. The fact that all forms of BMC when co-fertilised, and the N-enriched BMC4 generated equal or greater income than using inorganic fertiliser can help facilitate greater and more widespread adoption of liquefied BMC fertilisers.

Supplementary Information

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Supplementary Material 1.

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Author contribution

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Data availability
Data will be made available upon request.

Declarations

Competing interests
Zhihong Xu is an EBM of the journal Biochar, and he was not involved in the peer-review or handling of the manuscript. Authors report financial support was provided by Australian Research Council and declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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