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# Effects of Biochar-Based Fertilizer on Root Zeta Potential, Nutrient Leaching and Yield in an Intensive Protected Cropping System

Kane Trubenbacher [1,2], Shahla Hosseini Bai [1], Lakmini Dissanayake [1], Negar Omidvar [1], Stephen Joseph [1,3] and Michael B. Farrar [1,*]

1 School of Environment and Science, Griffith University, Nathan, Brisbane, QLD 4111, Australia; info@kanetrubenbacher.com (K.T.); s.hosseini-bai@griffith.edu.au (S.H.B.); lakmini.dissanayakekurugamage@griffithuni.edu.au (L.D.); n.omidvar@griffith.edu.au (N.O.); s.joseph@unsw.edu.au (S.J.)

2 Queensland Department of the Environment, Tourism, Science and Innovation, Dutton Park, Brisbane, QLD 4102, Australia

3 School of Materials Science and Engineering, University of New South Wales (NSW), Sydney, NSW 2052, Australia

* Correspondence: m.farrar@griffith.edu.au

**Abstract**

Rising global demand for food and fibre requires more efficient and sustainable fertilizer strategies. Biochar mineral complexes (BMC) are being developed for use as an organic alternative to conventional synthetic fertilizers, or to supplement conventional fertilizers applied at lower rates. Biochar can change electrochemical properties such as zeta potential (ZP) that influence nutrient use efficiency. However, the impact of BMCs on the ZP of plant roots remains unknown. This study investigated the effects of BMC on root zeta potential, nutrient leaching, and yield in an intensive protected cropping system. A novel BMC was developed and tested in four treatments: synthetic fertilizer, organic fertilizer, BMC with half-rate organic fertilizer, and BMC alone. Organic fertilizer significantly increased negative root ZP compared with other treatments, largely due to higher concentrations of –COOH and –OH functional groups on the potting media. Treatments containing organic fertilizer also increased pH and cation exchange capacity (CEC), enhancing nutrient availability and retention relative to synthetic fertilizer. Yield was greatest with synthetic fertilizer; however, BMC combined with half-rate organic fertilizer achieved similar yields to full-rate organic fertilizer. This indicates that BMC co-applied with half-rate organic fertilizer should be considered by farmers to be a viable alternative to full-rate organic fertilizer regimes to reduce net inputs and risk of negative environmental impacts from over-fertilization.

**Keywords:** biochar; biochar-mineral-complex; organic fertilizer; precision agriculture

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Academic Editors: Nick B. Comerford, Yafei Wang, Yizhe Dong, Zhixiong Tan, Longyao Zhang and Hui Zhang

Received: 4 September 2025
Revised: 3 October 2025
Accepted: 9 October 2025
Published: 13 October 2025

**Citation:** Trubenbacher, K.; Hosseini Bai, S.; Dissanayake, L.; Omidvar, N.; Joseph, S.; Farrar, M.B. Effects of Biochar-Based Fertilizer on Root Zeta Potential, Nutrient Leaching and Yield in an Intensive Protected Cropping System. *Land* **2025**, *14*, 2036. https://doi.org/10.3390/land14102036



## 1. Introduction

Food production must continue to increase in order to feed our projected population of 10 billion in 2050 [1]. The required increase in food production must occur despite additional global challenges including the changing climate, ongoing soil degradation and urbanization, and meeting net zero commitments despite high requirement for fertilizers, water, and energy inputs [2,3]. Industrial agriculture heavily depends on repeated and ongoing application of synthetic fertilizers that contain readily soluble nutrients required by crops to produce high yields [4]. Synthetic fertilizers can increase yield for staple crops by up to three times; however, ongoing use in the long-term leads to soil acidification and land degradation [5]. Also, misuse and over-application of synthetic fertilizers can result in environmental pollution from leaching and runoff [6,7]. Therefore, developing high efficiency fertilizers that minimize environmental impact while not compromising yield are an imperative for future agriculture to meet the required increase in demand.

Biochar mineral complexes (BMC) are a form of biochar-based fertilizer that are emerging commercially. Also known by other industry terms including commercial biochar fertilizer, organo-mineral biochar fertilizer, biochar-based fertilizer, and enriched biochar fertilizer, BMCs can be engineered or modified to meet specific agronomic outcomes and address known site–soil–crop challenges such as increasing a soil with low pH or cation exchange capacity (CEC) [8–10]. For example, if a soil is predominantly sand in texture, adding clays such as bentonite to the BMC mixture can help improve soil CEC after application [11,12]. Also, co-applying biochar and/or BMCs with organic fertilizers can increase nutrient use efficiency by lowering soil redox potential [13,14]. Developing modified biochar products, such as BMCs, and using advanced characterization techniques, can aid in understanding the electrochemical effects of biochar and BMCs being applied to agricultural systems [15]. However, understanding the effect that BMC has on the underlying mechanisms within soil–plant systems is critical to the continuing development of engineered BMC fertilizers.

Applying biochar and BMC fertilizers to soils can affect the electrochemistry of the soil and surrounding soil solution [13]. Zeta potential (ZP) is an electrophysical parameter that represents the average electrokinetic potential across the boundary between a solution and a particle, called the shear plane, similar to the boundary between a plant root and soil solution [16,17]. Zeta potential ($\zeta$) is measured in volts and within the plant–soil context, represents the potential difference (mV) between the soil solution and the root surface, and therefore indicates the nature of charge and adsorption capacity of the plant roots [18]. Zeta potential is determined while considering both the solid particle (root surface) and the solution medium (soil solution) in question [19]. Therefore, substances such as fertilizers or BMCs that are known to modify soil properties may also affect the ZP of plants root surfaces, because the ZP of root surfaces is dependent on rhizosphere electrochemistry [17]. Previously, applying wood biochar has increased the negative ZP for both mint and safflower crop roots by 42% and 31%, respectively [16]. Additionally, BMCs affect soil redox reactions, and changes to root membrane potential have been examined and shown to reduce the energy required for nutrient uptake [17]. However, to the best of our knowledge, there is no reported evidence regarding the effects of applying BMC or biochar-based fertilizers, rather than pure biochar, on the ZP of plant roots. Understanding the electrochemical effects of BMC on the plant–soil boundary may help to develop improved fertilizer products with additional agronomic benefits.

Root ZP is intercorrelated with both soil properties, such as pH, CEC and cation balance, and treatments applied to soil [9,16,20]. Soil pH directly moderates nutrient availability for plants, with most nutrients being available in between 5.5 and 6.5 pH [21]. Cation exchange capacity is the capability of a particle surface to adsorb and exchange cations via an electrostatic force [22]. Increased soil CEC improved plant productivity due to increased availability of nutrients in cation forms [3,23]. Specifically, potassium (K), calcium (Ca), and magnesium (Mg) are important cations for plant growth and are directly moderated by soil CEC [24]. Also, clays and organic matter both have high CEC, and adding those to a BMC mixture has the potential to increase the relative CEC of the BMC produced [25]. Therefore, understanding how BMC formulated with specific ingredients, including clays, would influence the ZP of plants is of great value for ongoing biochar-based fertilizer development.

This study used ginger (*Zingiber officinale*) as a model crop, which is widely planted in protected cropping systems to ensure crop quality. Ginger requires intensive water and nutrient management regimes, and therefore, is prone to nutrient leaching when grown in a soilless potting media system [26,27]. Zeta potential is a systemic indicator of electro-root zone chemistry, and therefore, understanding how different fertilizer regimes affect the electrochemistry of potting media systems would improve the potential to mitigate nutrient leaching and its detrimental environmental impacts. This study investigated the effects of a novel BMC fertilizer, and commercial organic and synthetic fertilizers on the electrochemical properties of potting media and ginger yield within a protected cropping system. We hypothesized that negative root ZP and CEC would increase under BMC application compared with synthetic fertilizer due to the increased content of biochar, organic matter, and clay, and that improvements in CEC and ZP would result in reduced nutrient leaching. Specifically, this study aimed to elucidate the effect of different fertilizer regimes on: (1) plant root zeta potential, (2) nutrient leaching, and (3) plant biomass yield. The results of this study will help develop novel biochar-based fertilizers and BMC products and inform best management practice for managing protected cropping systems.

## 2. Materials and Methods

### 2.1. Site Description

A pot trial was established in September 2023 at a certified organic farm, Little Bunya Organics, located in Kandanga, QLD, Australia (−26.376045, 152.691549). The pot trial was conducted using 20 L polyethylene bags as pots for all treatments. The farm provided a protected cropping nursery that was decertified of organic status to allow the application of synthetic fertilizers to sterilized potting media for growing disease-free ginger rhizomes for use as future propagation stock. The average annual maximum temperature during the study period was 27.2 °C and the average annual minimum temperature was 13.7 °C. The average annual rainfall was 1117.6 mm [28].

### 2.2. Experimental Design, Treatments and Establishment

The experiment was designed as a randomized block trial with four treatments and eight replicates per treatment. The four treatments used in this study were as follows: (1) "synthetic fertilizer" (S100): slow-release synthetic fertilizer blended into pine bark potting media by the manufacturer, this treatment represented the control and is current industry practice; (2) "organic fertilizer" (O100): organic fertilizer added at the full rate to the same pine bark potting media (15 t $ha^{-1}$ equivalent), this application rate represents current industry practice; (3) "BMC co-applied with half-rate organic fertilizer" (BMC + O50): BMC (1 t $ha^{-1}$) and half-rate organic fertilizer (7.5 t $ha^{-1}$) added to the same pine bark potting media; and 4) "BMC" (BMC): BMC (1 t $ha^{-1}$ ) added to the same pine bark potting media. BMC application rates were calculated to be financially viable for farm scale application. Application rates were also calculated in accordance with farmer practice, equating pot surface area to a fraction of a hectare. The pine bark potting media used in all treatments contained a basal dose of lime added by the manufacturer to adjust the media to a neutral pH prior to delivery. The organic fertilizer treatment was a proprietary blend of commercially available, organic certified products that included a pelletized chicken-manure fertilizer, lime in the form of $CaCO^{3-}$ and gypsum, and rock minerals used in organic ginger-cropping systems. The BMC was developed and manufactured by the authors, using low-temperature (400 °C) wheat straw and chicken manure (40:60) biochar specifically for use in ginger cropping. The biochar was blended with kaolin, bentonite, diatomite, apatite, magnetite, zeolite, basalt, iron (II) sulphate, manganese oxide, and titanium oxide. The ingredients used in the BMC were selected to maximize the positive impact on ginger nutrient cycling and yield compared to conventional organic fertilizers [9,29]. For example, apatite provides a stable form of phosphorous, kaolin can help mitigate abiotic stress and improve water retention, and zeolite is used to reduce the volatilization losses of nitrogen (N) [30–34]. Additionally, the boron (B) to zinc (Zn) ratio was tailored to be similar to the optimal 3:4.5 ratio required for maximum ginger yield [35]. Sub-samples of the potting media amended with each treatment were air-dried and analyzed for chemical functional groups using Fourier transform infrared (FTIR) spectroscopy (PerkinElmer FTIR Spectrum II, PerkinElmer USA). During FTIR analysis, spectra were recorded with a 16 $cm^{-1}$ spectral resolution between 450 and 4000 $cm^{-1}$. Details of chemical analysis and a summary of nutrients added to pots for all treatments are available in Tables 1 and 2, respectively.

**Table 1.** Physicochemical properties of the commercial potting medias, fertilizer and biochar mineral complex (BMC) used in the study.

| Parameter | Unit | Pine Bark Potting Media Base | Pine Bark Potting Media Enriched With Synthetic Fertilizer | Organic Fertilizer | BMC |
|---|---|---|---|---|---|
| Wet bulk density | kg $L^{-1}$ | 0.5 | 0.61 | n.a | n.a. |
| Dry bulk density | kg $L^{-1}$ | 0.25 | 0.31 | n.a | n.a. |
| Moisture content | % | 51 | 48 | n.a | 35 |
| Air-filled porosity | % | 22 | 17 | n.a | n.a. |
| Total water holding capacity | % | 53 | 58 | n.a | n.a. |
| pH | | 7.16 | 6.31 | n.a | 8.6 |
| Electrical conductivity | dS $m^{-1}$ | 0.16 | 2.4 | n.a | 26 |
| Chloride | mg $L^{-1}$ | 20 | 177 | n.a | n.a. |
| Ammonium nitrogen | mg $L^{-1}$ N | 1.3 | 28.2 | n.a | n.a. |
| Nitrate nitrogen | mg $L^{-1}$ N | 0.2 | 28.5 | n.a | n.a. |
| Total Carbon (C) | % | 32.6 | 34.3 | 18.3 | 33.3 |
| Total Nitrogen (N) | % | 0.2 | 0.6 | 5.21 | 5.52 |
| Calcium (Ca) | % | 0.63 | 1.2 | 14.18 | 1.39 |
| Magnesium (Mg) | % | 0.23 | 0.26 | 3.36 | 0.39 |
| Potassium (K) | % | 0.04 | 0.36 | 3.74 | 1.94 |
| Sodium (Na) | % | 0.04 | 0.08 | BDL | 0.76 |
| Sulphur (S) | % | 0.02 | 0.17 | 1.35 | 0.73 |
| Phosphorus (P) | %__tracked | BDL | 0.04 | 2.9 | 0.72 |
| Zinc (Zn) | % | BDL | 0.003 | 0.13 | 0.03 |
| Manganese (Mn) | % | BDL | 0.012 | 0.032 | 0.25 |
| Iron (Fe) | % | 0.25 | 0.96 | 3.13 | 3.59 |
| Copper (Cu) | % | BDL | 0.006 | 0.027 | 0.02 |
| Boron (B) | % | 0.02 | 0.02 | 0.25 | 0.01 |
| Silicon (Si) | % | BDL | BDL | 3.5 | 0.01 |
| Aluminum (Al) | % | 0.3 | 0.403 | BDL | 0.69 |

BDL: below detectable limit; Organic fertilizer (O100) nutrient analysis was provided by the manufacturer.

Prior to establishment commercial: (1) pine bark potting media containing synthetic fertilizer added by the manufacturer, and (2) identical pine bark potting media without added synthetic fertilizer were sourced from the same supplier. At the time of establishment, 20 L of potting media containing synthetic fertilizer (6200 g) was randomly added to each pot, ready for ginger planting. All other treatments were made by weighing and blending fertilizer treatments and/or BMC with the pine bark potting media (not containing synthetic fertilizer), using a 200 L compost mixer. BMC treatment was prepared by adding 48 g ($w/w$) granular BMC in a layer approximately 100 mm from the top of the pot and covered with the remaining potting media. Organic fertilizer treatments were pre-weighed and added to 20 L of base potting media (5000 g) and mixed using a compost mixer for 5 min until homogenized, before being added to each pot. BMC + O50 treatment was prepared by mixing 50% of pre-weighed organic fertilizer treatment (half-rate) with 48 g (*w*/*w*) of solid BMC with water to form a slurry that was poured over the entire potting media surface area.

**Table 2.** Nutrient content (g pot$^{-1}$) of different fertilizer treatments added to the base potting media and used in the study.

| Treatment | N (g pot$^{-1}$) | P (g pot$^{-1}$) | K (g pot$^{-1}$) | Ca (g pot$^{-1}$) | Mg (g pot$^{-1}$) | B (g pot$^{-1}$) | Zn (g pot$^{-1}$) |
|---|---|---|---|---|---|---|---|
| S100 | 51.2 | 3.3 | 31.3 | 100.0 | 21.6 | 1.8 | 0.4 |
| O100 | 38.0 | 20.9 | 22.0 | 102.7 | 24.3 | 1.7 | 0.2 |
| BMC + O50 | 28.9 | 11.8 | 14.0 | 73.8 | 22.1 | 1.6 | 0.2 |
| BMC | 17.4 | 1.4 | 5.1 | 46.5 | 19.7 | 1.5 | 0.1 |

S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with added biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex.

Disease-free ginger rhizomes were randomly selected from a clean rhizome planting stock provided by Little Bunya Organics. Each large rhizome was divided into smaller ~60 g pieces for planting with a sharp sterilized knife [36]. Each individual piece used for planting showed two or more unsprouted eyebuds [36]. Finally, each divided rhizome piece was randomly allocated to a prepared pot and was placed in the centre of the treated potting media ~5 cm below the surface. All pots were placed into the nursery in a randomized block design. Overhead irrigation was delivered 3 times daily for 20 min intervals, representing 5.2 mm day$^{-1}$ equivalent rainfall. Pots were re-randomized at weeks 14 and 22 and inspected for pests and weeds that were removed.

### *2.3. Sample Collection and Analysis*

To ensure maximum root development and allow for any morphological effects to manifest, ginger roots were harvested 35 weeks after planting in May 2024 [37]. At the time of harvest, incisions were made on two opposite sides of the pots allowing access to roots that had proliferated between the media and the pot surface. Approximately 10 g of adventitious root material was cut using a sharp stainless-steel knife and placed in paper bags for transport. A 100 g sample of potting media adjacent to where the roots were harvested from was collected using a glass spoon and stored in polyethylene bags for transport to the laboratory. After collection of root and potting media samples, pots were repaired using tape and returned to the nursery in waiting for the completion of senescence, when rhizomes are ready to be propagated and replanted into the next crop. Leachate samples were collected on two occasions at 14 and 22 weeks after establishment. Five pots were randomly selected for sampling from each treatment. To collect leachate samples, each pot was elevated over a large 40 L plastic bin, and 4 L of water was poured over the entire potting media surface area in a 1 min period. The pots were left to drain for 20 min when 50 mL of leachate solution was sub-sampled from each plastic collection pot and refrigerated at 4 °C for transport and storage [38]. Finally, 40 weeks after planting and in July 2024, ginger rhizomes were harvested from the pots by lifting them from the potting media. Rhizomes were brushed clean and weighed using a digital balance. Commercial value was calculated by multiplying reported market price by rhizome weight. Market prices were obtained for Brisbane wholesale markets in 2023 (Market Information Services, Brisbane Market, Rocklea). Net income was calculated by subtracting the cost of fertilizer treatments from the calculated commercial value per pot in Australian dollars. Income was expressed on a per-pot basis to reflect farmer practice in protected cropping systems. Fertilizer costs were derived by searching retail prices listed on manufactures' websites during October 2023.

In the laboratory, roots were brushed clean and washed twice using deionized water and then oven dried at 60 °C [39]. Potting media samples were air dried until they were a constant weight for 24 h. Potting media pH was determined by using the Test Methods for the Examination of Composting and Compost (TMECC) standard method for compost analysis, using a handheld sensor (labCHEM hydro sensor, TPS Pty Ltd., Brisbane, QLD, Australia) [40]. Exchangeable cations were extracted using the Barium Chloride method [41]. Total CEC was determined by the summation method [42]. The ratio of Mg relative to exchangeable Ca and K were calculated using the following Equation [43]:

$$\frac{\mathrm{Mg}}{(\mathrm{Ca}+\mathrm{K})} \tag{1}$$

Root surface ZP was measured using the streaming potential measurement method described by Li et al. [39]. In brief, ginger roots were treated as fibres and bundled into plugs for streaming potential analysis within a cylindrical cell [39]. Specifically, ~0.5 g of roots was cut into 3 cm in length and arranged into a cylindrical cell using tweezers. The roots were formed into a plug with even capillary spacing and 0.1 M KCl electrolyte solution was streamed across the cylindrical cell at 200 mbar, using the SurPASS operating procedure to measure streaming potential [44]. Once the electrical conductivity of the roots and electrolyte solution had reached equilibrium, streaming potential was measured. Zeta potential ($\zeta$) was calculated using the Helmholtz–Smoluchowski equation:

$$\mathrm{z} = \frac{dU}{dp} \cdot \frac{\mathrm{h}}{\varepsilon \cdot \varepsilon 0} \cdot KB \tag{2}$$

where $dU/dp$ = slope of streaming potential versus differential pressure, $\eta$ = electrolyte viscosity, $\varepsilon$ = dielectric coefficient of electrolyte, $\varepsilon_0$ = vacuum permittivity and $KB$ = electrolyte conductivity [44]. Following analysis of each sample, the electrolyte solution was purged and replaced with a buffer solution, the instrument recalibrated and the sample discarded. The measurement process was repeated for six replicates of roots for each fertilizer treatment in the study to minimize variability. Zeta potential calculations were performed in VisioLab for SurPASS proprietary software (Anton Paar GmbH., Graz, Austria).

### *2.4. Statistical Analysis*

One-way analysis of variance (ANOVA) was used to identify differences among treatments and treatment effects were determined at $p < 0.05$. Tukey HSD post hoc was used for comparison of means where ANOVA determined significant differences among treatments. Analysis of covariance (ANCOVA) was used to determine the significance of pH on ZP. Linear regression models with confidence intervals of 95% were calculated to examine relationships between pH and zeta potential, and proportional Mg concentration and rhizome yield. All statistical analysis was performed using R4.3.2 in the RStudio V1-494 environment (R-Studio., Boston, MA, USA).

## 3. Results

### *3.1. FTIR Analysis of Biochar Mineral Complex and Potting Media*

Spectroscopic analysis using FTIR detected higher peaks representing carboxylic acid (C–O stretching) between 1265 and 1430 $\mathrm{cm}^{-1}$ for BMC and organic fertilizer compared with synthetic fertilizer (Figure 1). Distinct peaks representing carboxylic acid (C=O stretching) were observed at 1630 $cm^{-1}$ for all treatments and the peak for organic fertilizer (0.085 a.u) and BMC (0.065 a.u) were higher than synthetic fertilizer (0.039 a.u) (Figure 1). Broad peaks at 3300 $cm^{-1}$ were detected for all treatments corresponding to O–H stretching and formation of carboxylic acid groups (Figure 1). Intensity of the broad peak at 3300 $cm^{-1}$ was lower for BMC and synthetic treatments compared with organic fertilizer (Figure 1).

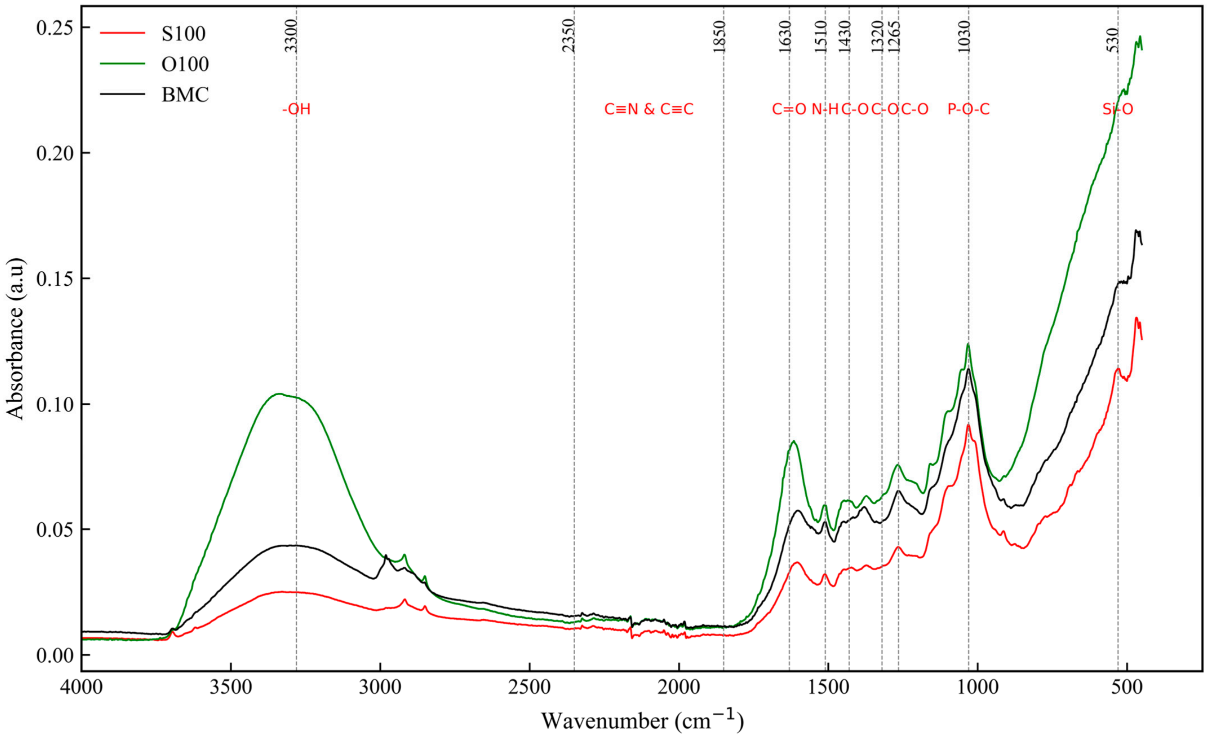


**Figure 1.** Fourier transform infrared (FTIR) absorbance spectrum of treatments used in the study. S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC: potting media with biochar mineral complex.

### *3.2. Plant Root and Rhizosphere Electrochemistry, Cation Exchange Capacity and Balance and Concentration of Cations in Leachates*

Applying organic fertilizer increased negative root ZP (−9.97 mV) compared with applying BMC (−4.71 mV) or synthetic fertilizer (−2.72 mV) (Figure 2). Negative root ZP was similar for plants grown using organic fertilizer and BMC co-applied with half-rate organic fertilizer (Figure 2).

Applying synthetic fertilizer to potting media decreased pH compared with all other treatments (Figure 3a). Potting media treated using BMC co-applied with organic fertilizer had a higher pH compared with potting media treated with organic fertilizer alone (Figure 3a). Cation exchange capacity was higher for potting media treated with organic fertilizer (+19.7%) and BMC co-applied with organic fertilizer (+18.5%) compared with applying synthetic fertilizer (Figure 3b). Additionally, exchangeable cation concentrations varied between treatments for Mg and Ca, but not K (Figure 4). Specifically, exchangeable Mg concentration was higher for all other treatments compared with synthetic fertilizer (Figure 4a). Exchangeable Ca concentration was higher in potting media treated with synthetic and organic fertilizer compared with BMC, and exchangeable K was similar among all treatments (Figure 4b,c). Potting media amended with BMC had higher exchangeable Mg by proportion compared with all other treatments (Figure 5a). The BMC amendment increased proportion of exchangeable Mg concentration by 187%, 30%, and 15% compared with synthetic fertilizer, organic fertilizer, and BMC co-applied with half-rate organic fertilizer, respectively (Figure 5a).

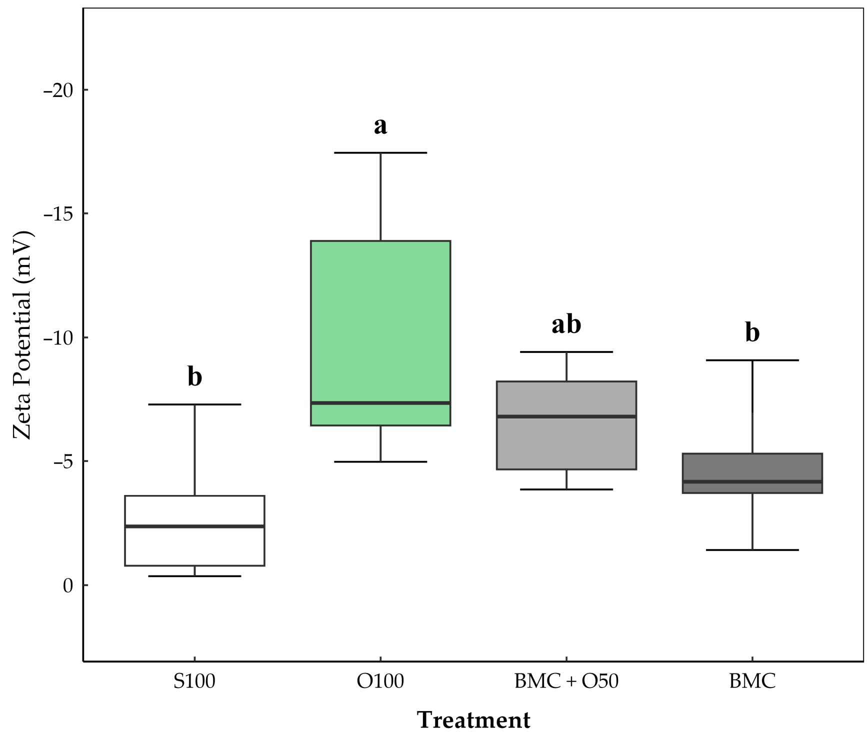


**Figure 2.** Zeta potential (mV) of ginger roots grown using the different treatments in the study; S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex. Different lowercase letters indicate significant difference between treatments Tukey's HSD ($p < 0.05$). The central horizontal line within each box represents the median, boxes represent the interquartile range, and error bars indicate minimum and maximum values.

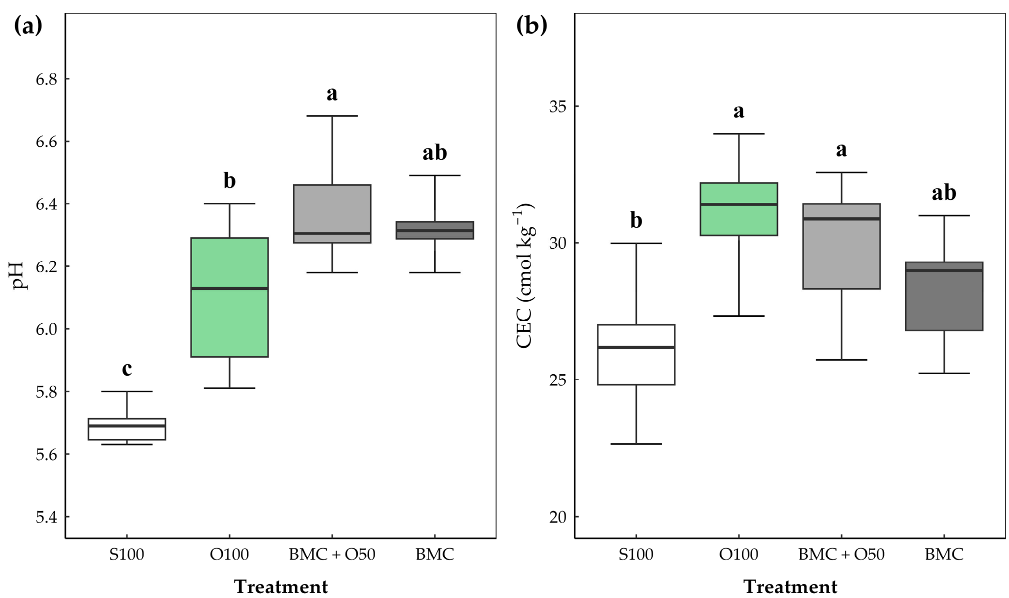


**Figure 3.** (**a**) pH of potting media and (**b**) cation exchange capacity of potting media under different treatments; S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with added biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex. Different lowercase letters indicate significant difference between treatments Tukey's HSD ($p < 0.05$). The central horizontal line within each box represents the median, boxes represent the interquartile range, and error bars indicate minimum and maximum values.

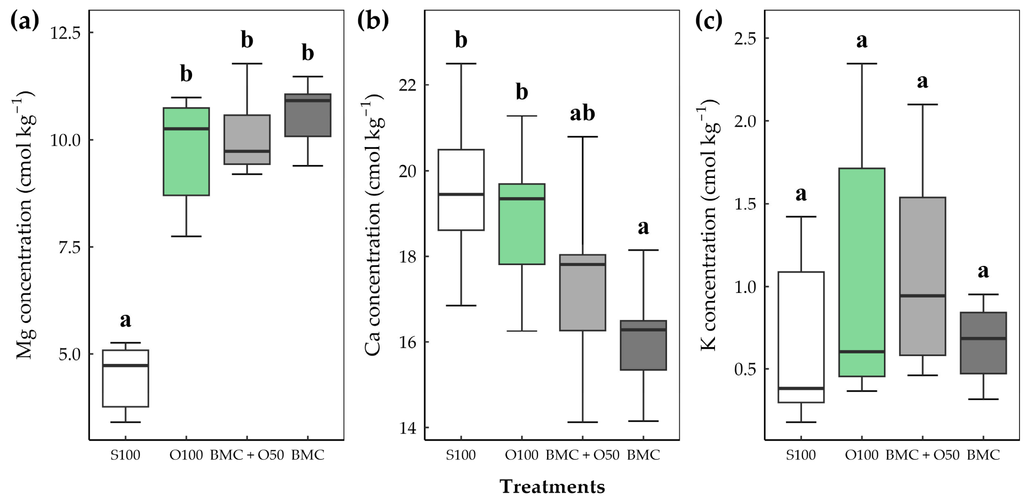


**Figure 4.** Concentrations of exchangeable (**a**) Mg (**b**) Ca and (**c**) K ions in potting media under different treatments; S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with added biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex. Different lowercase letters indicate significant difference between treatments Tukey's HSD ($p < 0.05$). The central horizontal line within each box represents the median, boxes represent the interquartile range, and error bars indicate minimum and maximum values.

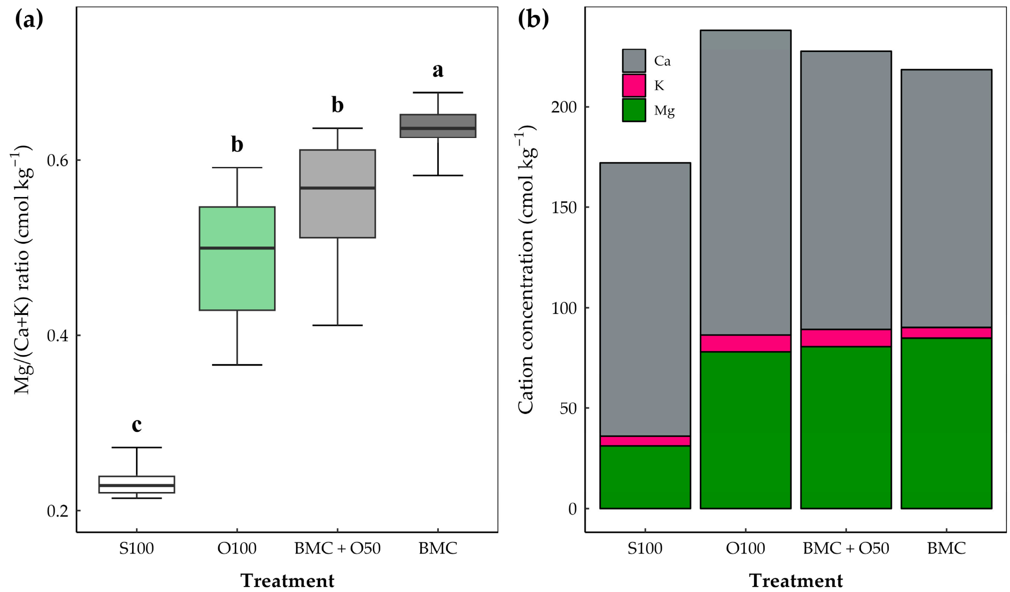


**Figure 5.** (**a**) Proportion of exchangeable Mg concentration relative to Ca and K; and (**b**) total exchangeable Ca, K and Mg fractions contained within potting media with different added treatments; S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with added biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex. Different lowercase letters indicate significant difference between treatments Tukey's HSD ($p < 0.05$). The central horizontal line within each box represents the median, boxes represent the interquartile range and error bars indicate minimum and maximum values.

Applying synthetic fertilizer to potting media increased the concentration of $NH_4^+$-N leached from pots at weeks 14 and 22 compared with all other treatments (Table 3). Leached $NO_3^-$-N concentration was highest from potting media amended with synthetic and organic fertilizer when BMC was not co-applied (Table 3). Leached $NH_4^+$-N and $NO_3^-$-N concentrations from synthetic fertilizer pots were highest at week 14 compared with all other treatments, and all other treatments were similar for both weeks 14 and 22 (Table 3).

**Table 3.** Ammonium ($NH_4^+$-N) and nitrate ($NO_3^-$-N) concentrations (mg $L^{-1}$) in water leached through pots at weeks 14 and 22.

| Treatment | Week 14 | | Week 22 | |
|---|---|---|---|---|
| | $NH_4^+$-N (mg $L^{-1}$) | $NO_3^-$-N (mg $L^{-1}$) | $NH_4^+$-N (mg $L^{-1}$) | $NO_3^-$-N (mg $L^{-1}$) |
| S100 | 0.88 ± 0.15 a | 33.53 ± 10.95 a | 0.32 ± 0.05 a | 8.28 ± 4.12 a |
| O100 | 0.34 ± 0.07 b | 10.16 ± 5.46 ab | 0.16 ± 0.01 b | 0.95 ± 0.22 a |
| BMC + O50 | 0.25 ± 0.05 b | 0.83 ± 0.29 b | 0.08 ± 0.01 b | 0.64 ± 0.12 a |
| BMC | 0.09 ± 0.01 b | 0.22 ± 0.07 b | 0.12 ± 0.01 b | 0.44 ± 0.06 a |

S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with added biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex. Different lowercase letters indicate significant difference between treatments Tukey's HSD ($p < 0.05$).

### 3.3. Biomass Yield and Economic Value of Ginger Rhizomes

Plants grown in potting media amended with synthetic fertilizer had higher ginger rhizome yield compared with rhizomes grown in potting media amended with full-rate organic fertilizer (+51%), BMC co-applied with organic fertilizer (+102%) and BMC (+1008%) (Figure 6a). Yield was similar for plants grown using organic fertilizer or BMC co-applied with half-rate organic fertilizer (Figure 6a). Applying BMC alone without additional fertilizer decreased rhizome yield compared with all other treatments (Figure 6a). Rhizome yield was negatively correlated with Mg concentration and there was a significant linear relationship (y = −3961.8x + 3039.5, $p$ = 1.75 $e^{-11}$) between the variables (Figure 6b).

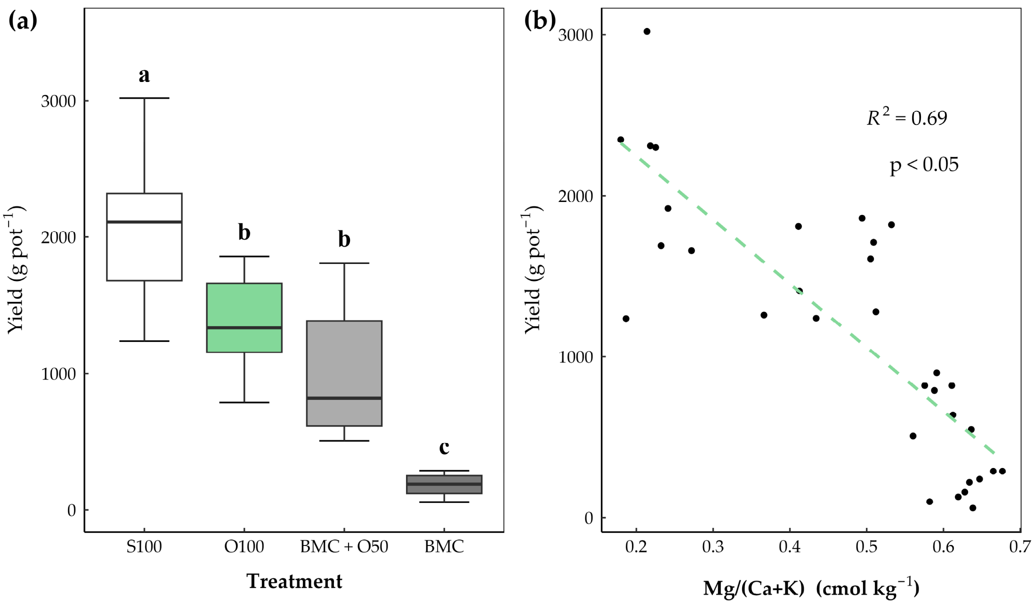


**Figure 6.** Biomass yield (**a**) of ginger rhizomes grown using the different treatments, and (**b**) scatterplot and linear regression model for ginger rhizome yield relative to the proportion of exchangeable Mg. S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with added biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex. Different lowercase letters indicate significant difference between treatments Tukey's HSD ($p < 0.05$). The central horizontal line within each box represents the median, boxes represent the interquartile range, and error bars indicate minimum and maximum values.

Rhizomes grown using synthetic fertilizer had higher net income per pot compared with using full-rate organic fertilizer, BMC co-applied with organic fertilizer and BMC (+16, +60%, and +3030%, respectively) (Table 4). Net income per pot using organic fertilizer and BMC co-applied with half-rate organic fertilizer treatments were similar, while net income per pot for the BMC treatment was not financially viable at \$1 pot$^{-1}$ (Table 4).

**Table 4.** Cost benefit analysis of the impacts of different treatments on ginger rhizome yield.

| Treatment | Commercial Value (\$ pot$^{-1}$) | Net Income (\$ pot$^{-1}$) | Cost of Fertilizer and Potting Media (\$ pot$^{-1}$) |
|---|---|---|---|
| S100 | 34.63 ± 3.1 a | 30.28 ± 3.1 a | 4.33 |
| O100 | 29.92 ± 2.9 ab | 26.09 ± 2.9 a | 3.85 |
| BMC + O50 | 22.38 ± 3.8 b | 18.87 ± 3.8 a | 3.52 |
| BMC | 4.14 ± 0.6 c | 1.04 ± 0.6 b | 3.08 |

S100: potting media with synthetic fertilizer; O100: potting media with organic fertilizer; BMC + O50: potting media with added biochar mineral complex co-applied with half-rate organic fertilizer; BMC: potting media with biochar mineral complex. Different lowercase letters indicate significant difference between treatments Tukey's HSD ($p < 0.05$).

## 4. Discussion

This study identified that root zeta potential did not explain changes in yield. Interestingly, yield was similar for ginger grown using BMC co-applied with organic fertilizer and full-rate organic fertilizer, despite containing lower nutrient inputs. Ginger grown using synthetic fertilizer had higher yield than ginger grown with all other fertilizer treatments examined. However, despite having higher yield, applying synthetic fertilizer did not increase net income compared with full-rate organic fertilizer and BMC co-applied with organic fertilizer. The net income similarities indicate that ginger production can be carried out under organic certification and with reduced fertilizer inputs, whilst not negatively impacting farm income.

### *4.1. Effects of Fertilizer Treatments on Electrochemistry of Plant Roots and Potting Media*

Zeta potential of plant roots grown with organic fertilizer had higher negative root ZP compared with BMC or synthetic fertilizer. However, the ZP of roots grown in BMC co-applied with half-rate organic fertilizer was similar to organic fertilizer, indicating that the change in root ZP was driven by applying organic fertilizer rather than BMC. In a previous study, applying pure wood biochar increased the negative root ZP of safflower and mint roots by 31 and 42%, respectively [16]. The increased negative root ZP for safflower and mint roots is explained by increased production of negatively charged functional groups (carboxyl groups) present on the cell walls of plant roots [16]. Our results were contradictory and did not support BMC affecting the ZP of ginger roots [16]. Some important distinctions may explain the disparity: (1) the effective rate of biochar application was 3600% less in this study (36 t ha$^{-1}$ vs. 1 t ha$^{-1}$), (2) the two studies used biochar made from different feedstocks (maple wood vs. chicken manure), and therefore have different electrochemical properties and reactivity, and (3) the previous study used a soil, whereas this study used a sterile potting media devoid of many important biotic and abiotic features present within soils that mechanistically influence electrochemistry [17,34,45]. We suggest that to detect a measurable change in ginger root ZP, higher application rates of BMC are required (>1 t ha$^{-1}$).

Secondly, the novel BMC was developed using additional clays and minerals and applied at a low rate to reduce costs compared to using pure wood biochar at rates that are not economical, but have previously increased ZP [16]. BMCs possess high proportions of negatively charged functional groups and their subsequent deprotonation within soil or potting media can increase root electronegativity [46,47]. In this study, BMC contained 57.14% greater abundance of –C=O and 74.00% greater abundance of –OH than the synthetic fertilizer treatment. Recently, a study that applied micronized BMC (<25 um) demonstrated increased root cell negative potential, highlighting the potential of BMC to increase nutrient uptake and changes to nutrient gene expression [10]. However, the total number of effective functional groups available for root exchange also increases the negative root ZP and has been attributed to the production and deprotonation of –COOH, –OH, and –$H_2PO_4$ functional groups on the root surface [16,18,20,48]. High concentrations of –COOH, –OH, and –C=O in O100 compared to concentrations in S100 could explain the differences in both CEC and ZP between the two treatments. The BMC in this study contained negatively charged functional groups –COOH, –OH, and –C=O identified by FTIR. However, the low application rate we used (1 t $ha^{-1}$) reduced the total number of active functional groups and can explain why an effect was not found. Intercalation of organic carbon by clay contained within BMC can enhance the stability of the organic carbon and prolong the production of -COOH groups over time [49]. In a previous incubation study, the number of -COOH, -C-O, and -OH functional groups in BMC increased over 49 days because of clay intercalation of organic carbon [47]. Therefore, BMC can be used as an effective amendment to increase negative functional groups over time, while being more economically feasible than the high-rate application of pure biochar.

The surface electronegativity of a BMC can increase because of interactions between the biochar and additional clays during torrefaction [50,51]. Feedstock and the pyrolysis temperature of the biochar can also have a profound effect on its CEC [52,53]. Biochar present in BMC can increase CEC by increasing surface area, negative surface charge, and charge density [10,54,55]. In this study, the biochar was produced using a feedstock of chicken manure and wheat straw, and at low (400 °C) highest temperature of treatment during pyrolysis. Chicken manure biochar pyrolyzed at low temperatures (<450 °C) have high CEC, due to the retention of H- and O- functional groups on the biochar surface [56]. High initial cation concentrations within chicken manure can catalyze the formation of O- functional groups on the biochar surface during pyrolysis [24]. The increase in O-functional groups can then increase the soil/potting media CEC after application [52]. Another mechanism contributing to higher CEC in BMC co-applied with organic fertilizer rather than synthetic fertilizer was the addition of clays kaolin and bentonite. The addition of clays and silicate materials to BMCs can further increase CEC of the parent biochar [50]. Clays present in BMC can convert aromatic carbon rings to C-O functional groups on the biochar surface, increasing adsorption characteristics of the biochar [12]. Bentonite is also a high activity smectite clay with a high CEC [57]. Our study suggested that co-applying BMC affects CEC even when applied at low rates.

### 4.2. Effects of Fertilizer Treatments on Ginger Yield

Ginger yield and net economic return was the highest in the synthetic fertilizer (~\$30 $pot^{-1}$); however, similar yield was possible when co-applying BMC with half-rate organic fertilizer (~\$26 $pot^{-1}$) or using full-rate organic fertilizer (~\$19 $pot^{-1}$). Ginger plants require nutrients in the following decreasing order: N > K > Ca > Mg > S > P > Fe > Zn > B [58]. Therefore, increased yield in the synthetic fertilizer could in part be explained by higher basal N and K application rates than in other treatments. The synthetic fertilizer contains soluble N in a form that is readily available for plant use [59]. Unsurprisingly, the synthetic fertilizer treatment also resulted in highest $NH_4^+$-N leaching at weeks 14 and 22, and highest $NO_3^-$-N leaching at week 14 compared with all other treatments. Leachates from the synthetic fertilizer treatment indicate that N leaching is a potential environmental issue for the ginger industry to improve protected cropping practices [60].

Additionally, $NO_3^-$-N is the primary form of plant available N within soilless systems, making it's conservation important for the agronomic bottom line [61]. Therefore, although plant-available $NO_3^-$-N in synthetic fertilizer drove increases in yield, it also increased the environmental footprint and impacts associating with N leaching.

BMC co-applied with half-rate organic fertilizer had similar yield and commercial value to full-rate organic application, despite having significantly less initial N (−31.4%), K (−58.3%), Ca (−34.8%), Mg (−10%) and P (−76.9%) inputs compared with full-rate organic fertilizer. The soilless system used in this study combined a pine bark potting media with frequent overhead irrigation and rainfall, which are factors known to promote leaching [61]. Therefore, maintaining correct nutrient ratios is important, because correct nutrient balance is correlated with yield [61]. In our study, ginger yield decreased as proportional Mg concentration increased. Disproportionate quantities of Mg can induce deficiencies in other cations, especially K and Ca, which are important for ginger growth [62,63]. Nutrient deficiency caused by nutrient antagonism is one of the most common factors in divalent cations such as $Mg^{2+}$ when nutrient ratios are imbalanced [63–65]. Balancing Ca, Mg, and K cations by reducing Mg/K and Ca/K ratios leads to an improvement in K nutrition and yield in protected cropping systems [66]. In potting mediums with high K concentrations, K uptake has been significantly reduced by the addition of $Mg^{2+}$ [67]. Ginger requires high quantities of K during accelerated growth phases, and as such, yield may be reduced in growth mediums with high $Mg^{2+}$ concentrations [58]. The BMC we developed contained bentonite, a smectite clay that exhibits preferential adsorption of Mg cations [68]. Smectite clays have a specific affinity for $Mg^{2+}$ at the clay edge surface that diminish adsorption of cations of equal and lesser charge in electrolyte solutions [68,69]. Therefore, we suggest that the co-applied BMC may have contributed to Mg adsorption, leading to reduced availability of K and Ca for plant uptake and accumulation.

### *4.3. Practical Implications and Benefits of This Research*

Developing BMCs for site- and plant-specific applications can offer multiple benefits, including reduced requirement for traditional fertilizers while minimizing nutrient leaching, and downstream environmental impacts [9]. Our results support other studies that identified a significant role for biochar products such as BMC for use within sustainable agriculture [29,36,69–71]. Increasing adoption of biochar products can reduce the environmental footprint of agriculture by increasing carbon sequestration [29,72]. By adjusting the ingredients contained within BMCs that specifically affect functional groups and soil–plant parameters including ZP, CEC, and pH, we can enhance the potting media or soils' ability to ad/absorb nutrients, and also the plant's ability to utilize nutrients [10,14,71], therefore increasing yield, economic efficiency, and sustainability, and reducing leaching due to better alignment and optimization for delivery to plants [73]. This study also demonstrated that BMC applied alone at such a low rate without any fertilizer co-application was not sufficient for commercial ginger production, although ginger grown using BMC co-applied with reduced (50% less) rate organic fertilizer had similar yield and net commercial value at harvest to organic fertilizer applied at the full rate. Therefore, organic farmers should co-apply BMC with traditional organic fertilizer at a reduced rate or with another certified nutrient source to maintain yield.

## 5. Conclusions

The zeta potential of root surfaces in this study was affected by the treatments. Changes in ZP, however, did not drive changes in yield. BMC co-applied with organic fertilizer had similar yield and lower environmental footprint compared with using a full-rate organic fertilizer regime, because of lower initial N (−31%), P (−77%), and K (−58%) inputs, respectively. This study supports the potential for co-applying BMC with organic fertilizers in protected cropping systems to reduce fertilizer application rates. BMC can be applied to soilless systems that use potting media to help reduce the cost of nutrient inputs without sacrificing ginger yield.

**Author Contributions:** Conceptualization, K.T., M.B.F., S.H.B. and S.J.; methodology, K.T., M.B.F., S.H.B. and N.O.; software, K.T., M.B.F.; validation, K.T., M.B.F., N.O. and L.D.; formal analysis, K.T.; writing—original draft preparation, K.T.; writing—review and editing, M.B.F., S.H.B., N.O. and S.J.; visualization, K.T. and M.B.F.; supervision, M.B.F., S.H.B. and N.O.; project administration, M.B.F. and S.H.B.; funding acquisition, M.B.F. and S.H.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was jointly funded by the Australian Research Council (ARC) linkage (LP210200708), Griffith University, Rainbow Bee Eater Pty Ltd. and Little Bunya Organics.

**Data Availability Statement:** The data presented in this study are available upon request to the corresponding author (M.F.).

**Acknowledgments:** The authors acknowledge and sincerely thank Jess and Jesse Joyce for providing nursery access and management; Lei Guo and Hafiz Hosen for assistance with fieldwork; Alan White, Rad Bak, Sarah Keselj Davies and the team at Griffith Analytical Facility the Australian National Fabrication Facility for technical expertise and guidance.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| BMC | Biochar mineral complex |
| CEC | Cation exchange capacity |
| FTIR | Fourier transform infrared |
| ZP | Zeta potential |

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