

Biochar formulation determines soil improvement and fertiliser synergy during *Eucalyptus globulus* plantation establishment

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Abstract

Biochar produced from forest biomass residues can link renewable bioresource valorisation, soil improvement and fertiliser-use efficiency in planted forests. This study evaluated a high-carbon Biochar Pure and a mineral-enriched Biochar Plus, applied with and without mineral fertilisation, in an acidic Mediterranean *Eucalyptus globulus* plantation in central Portugal. Six treatments were assessed in the flat area and three in the terraced area, each with three replicated blocks. Mineral fertilisation increased plant height by 57% at 5 months and 117% at 12 months relative to the unfertilised control. Biochar Pure alone produced no growth response, whereas Biochar Plus without NPK increased height by 29% and 75%, respectively. Combined treatments produced the strongest response, reaching + 175% at 12 months. A descriptive Biochar–Fertiliser Synergy Index of 1.50 indicated a supra-additive response for Biochar Pure combined with mineral fertilisation. Biochar increased soil pH by 0.3–0.6 units at the first post-planting sampling, organic carbon concentration by 46–52% at 12 months, and cation exchange capacity by 81–108% at the first sampling. The Forest Soil Quality Index reached 0.770, while the Integrated Eucalypt Growth Index peaked at 1.525, showing that improved soil condition translated most strongly into plant performance when biochar was combined with fertilisation. Overall, *Eucalyptus*-derived biochar improved soil chemical condition and enhanced fertilisation efficiency during early plantation establishment. The findings support its use as a functional forest bioproduct for soil regeneration and circular biomass utilisation in Mediterranean fibre-production systems.

1. Introduction

Soil is a fundamental and non-renewable resource underpinning forest productivity, ecosystem functioning, and long-term land sustainability. In managed forest systems, soil chemical conditions strongly influence stand establishment, nutrient availability, and resistance to degradation processes, making soil quality a central component of forest ecosystem health (Krull et al., 2003; Madeira et al., 2012). This is particularly relevant in Mediterranean regions, where forest plantations are frequently established on acidic, nutrient-poor soils with limited buffering capacity and strong seasonal climatic variability and constraints (Gholamahmadi, 2026a).

In Portugal, *Eucalyptus globulus* plantations occupy extensive areas and are often managed under conditions where early nutrient limitation can restrict initial plant development and delay stand establishment (Fabres et al., 2005; Madeira et al., 2012). Improving soil conditions in such systems is, therefore, not only a silvicultural issue but also part of broader efforts to promote sustainable land management and maintain terrestrial ecosystem function. There is growing interest in soil amendments that can complement conventional fertilisation while contributing to more circular and resource-efficient forest management.

Among these, biochar has received substantial attention due to its potential to improve soil properties while providing a stable form of carbon in the soil (Lehmann et al., 2006; Nguyen et al., 2009; Woolf et al., 2010; Smith, 2016; Biswal and Balasubramanian, 2025). Produced by the thermochemical conversion of

biomass under oxygen-limited conditions, biochar is typically characterised by alkaline pH, aromatic carbon stability, and a porous structure with high surface reactivity, although its final properties depend strongly on feedstock and pyrolysis conditions (Singh et al., 2010; Sohi et al., 2010; Lehmann and Joseph, 2015; Mncedi et al., 2024).

These characteristics explain its proposed capacity to modify soil acidity, nutrient retention, cation exchange processes, and water-related functions (Spokas et al., 2012), with implications for plant performance and soil health (Borchard et al., 2014; Blanco-Canqui, 2017; Schmidt et al., 2021; Khan et al., 2024). Recent developments have further positioned engineered biochar as a versatile biomass-derived functional material for environmental applications, including soil amendment and carbon management (Asif et al., 2025). A substantial body of agricultural research has shown that biochar can enhance soil quality and productivity, although responses are highly context-dependent.

Meta-analyses have reported that positive yield effects tend to be stronger in acidic and degraded soils and often become more pronounced when biochar is combined with fertilisation rather than applied alone (Jeffery et al., 2011; Ye et al., 2016; Jeffery et al., 2017; Schmidt et al., 2021). Reviews have further highlighted improvements in soil pH, nutrient cycling, microbial activity, and organic matter dynamics, particularly where biochar is used as part of integrated soil management rather than as a direct fertiliser substitute (Agegnehu et al., 2017; Prodana et al., 2021; Xu et al., 2023; Ali et al., 2025).

Recent evidence also suggests that interactions between biochar and mineral or organic fertilisers can create synergistic responses by combining immediate nutrient supply with improved nutrient retention and a more favourable rooting environment (Chan et al., 2008; Van Zwieten et al., 2010; Agegnehu et al., 2017; Yang et al., 2025). These combined effects are especially relevant in nutrient-limited systems, where biochar may function less as a nutrient source per se and more as a soil conditioner that improves fertilisation efficiency.

Despite this broad literature base, forestry applications remain comparatively underdeveloped. Biochar research has historically been dominated by agricultural systems, while field evidence from forest plantations, especially under Mediterranean conditions, is still limited (Antonangelo et al., 2025; Bruckman et al., 2016; Bruckman and Pumpanen, 2019; Stavi, 2013; Thomas and Gale, 2015). This is a notable gap because forestry systems differ substantially from annual crops in rooting depth, nutrient cycling, time horizons, and management objectives.

In *Eucalypt* plantations, early establishment is particularly sensitive to nutrient imbalance (Verheijen et al., 2022), yet few studies have assessed whether biochar can improve soil conditions sufficiently to support young trees under operational field conditions. This is especially important considering increasing interest in valorising forestry residues through biochar production, thereby linking plantation management with circular bioeconomy strategies and climate mitigation efforts (Wrobel-Tobiszewska et al., 2015; Homagain et al., 2016; Bastos et al., 2025; Pérez et al., 2025).

In forest systems, the relevance of biochar extends beyond productivity alone. Biochar may contribute to sustainable forest management not only through carbon storage but also through its capacity to improve the functioning of planted soils and reduce dependence on external inputs under challenging site conditions (Thomas and Gale, 2015; Bruckman et al., 2016; Antonangelo et al., 2025).

Against this background, the present study evaluated a field biochar trial established in a Mediterranean *Eucalyptus globulus* plantation on acidic forest soil in central Portugal. In this context, *Eucalyptus*-derived biochar can be viewed not only as a soil amendment but also as a functional forest bioproduct that links biomass residue valorisation with soil regeneration and plantation establishment in fibre-production systems. Two woody biochars, a Pure biochar and a mineral-enriched “Plus” biochar, were tested with and without conventional mineral fertilisation in flat and terraced plantation areas.

We tested four hypotheses: H1, biochar improves early *Eucalypt* growth by increasing soil pH and improving soil nutrient status; H2, biochar enhances fertilisation efficiency, resulting in stronger growth responses when combined with mineral fertilisation than when applied alone; H3, biochar effects differ between flat and terraced areas because of contrasting baseline soil conditions and treatment structure; and H4, mineral-enriched Biochar Plus can partially substitute for conventional mineral fertilisation during early establishment, producing a stronger growth response than Pure biochar alone and approaching the response obtained with mineral fertilisation. By linking biochar product characteristics, soil nutrient responses and early plant development under operational field conditions, this study distinguishes soil-conditioning and fertiliser-synergy and provides evidence on the use of forest-residue-derived biochar as a functional bioproduct for circular *Eucalyptus* plantation management.

2. Materials and Methods

2.1 Study site

The field trial was established in Vale Domingos in Águeda, central Portugal (40°35'03.54" N 8°25'20.02" W) in June 2016. The field is representative of a Mediterranean forest region characterised by mild, wet winters and dry summers. Mean annual precipitation ranges between approximately 1,200 and 1,400 mm, with strong seasonal variability typical of Atlantic–Mediterranean transitional climates. The flat and terraced trial areas were located within the same Vale Domingos experimental site, allowing comparison under the same local climatic setting but contrasting micro-topographic and baseline soil conditions. The study site, experimental layout, and installation process are shown in Fig. 1.

2.2 Soil and biochar characteristics

The soil at the site is generally acidic, with low cation exchange capacity (CEC) and base saturation, reflecting common conditions in managed *Eucalyptus globulus* plantations in Portugal (Fabres et al., 2005; Madeira et al., 2012). Compared to the flat area, the terraced area had substantially higher topsoil organic matter content (1.58-fold), clay content (1.60-fold), CEC (1.67-fold), and base saturation (1.36-

fold). From the particle size distribution analysis, the soils of both the flat and terraced areas are classified as a sandy loam according to the USDA taxonomy. The physical and chemical characteristics of the soil are presented in Table 1.

Table 1

General physical and chemical characteristics of the soils in the trial areas. Reference ranges established by Fabres et al. (2005) for eucalypt stands are included for comparison.

Parameter	Units	Flat area 0–20 cm	Flat area 20–40 cm	Terrace area 0–20 cm	Terrace area 20–40 cm	Reference Range
Coarse Sand	%	38.9	36.5	20.1	21.1	–
Fine Sand	%	30.9	29.5	17.9	16.7	–
Silt	%	13.0	17.0	34.4	35.9	–
Clay	%	17.2	17.0	27.6	26.3	–
pH (H ₂ O)	–	5.2	5.1	4.9	5.0	–
Organic Matter	%	6.5	6.3	10.3	14.2	–
Total N	%	0.2	0.2	0.5	0.5	–
P	mg kg ⁻¹	6.6	5.7	7.9	7.9	10–25
Exchangeable Ca	cmolc kg ⁻¹	0.1	0.1	0.2	0.3	0.35–0.80
Exchangeable Mg	cmolc kg ⁻¹	0.2	0.1	0.5	0.7	0.1–0.2
Exchangeable K	cmolc kg ⁻¹	0.1	0.1	0.2	0.2	0.103– 0.192
Exchangeable Na	cmolc kg ⁻¹	0.1	0.1	0.1	0.1	–
Effective CEC	cmolc kg ⁻¹	3.1	2.5	5.1	5.7	–
Effective base saturation	%	13.7	14.5	18.6	24.2	–
Zn	mg kg ⁻¹	1.3	1.1	2.8	3.4	0.2–10
Cu	mg kg ⁻¹	0.5	0.6	1.5	1.8	0.5–5.0
Mn	mg kg ⁻¹	1.3	0.8	5.4	6.4	80–300
Fe	mg kg ⁻¹	139.2	130.7	170.6	154.2	10–40
B	mg kg ⁻¹	0.7	0.8	1.1	0.9	0.1–0.5

Two commercial forest-residue-derived biochar products, supplied by a commercial biochar producer in Portugal whose identity has been withheld for double-anonymous review, were tested: a standard biochar “Pure” and a mineral-enriched biochar “Plus”. Both were produced by slow pyrolysis of *Eucalypt* biomass residues. The Biochar Pure product had a pH (H₂O) of 9.7, a total carbon content of 78.0%, and moderate levels of exchangeable bases. The “Plus” biochar was deliberately enriched with mineral nutrients during production, resulting in a pH of 10.0, total carbon content of 61.1%, and markedly higher concentrations of exchangeable magnesium (Mg), potassium (K), sodium (Na), zinc (Zn), copper (Cu) and iron (Fe). The detailed chemical composition of both biochars is presented in Table 2. Additional characterisation of the biochar, including heavy metals and microbiological safety, as well as compliance with European Biochar Certificate (EBC) thresholds, is provided in Tables S4 and S5 (Supplementary Information).

Table 2
General physical and chemical characteristics of the biochar products tested in the trials, according to the technical sheet of products.

Parameter	Unit	Biochar Pure	Biochar Plus
pH (H ₂ O)	-	9.7	10
Carbon	%	78.04	61.12
Exchangeable Ca	cmol ⁺ kg ⁻¹	5.5	5.12
Exchangeable Mg	cmol ⁺ kg ⁻¹	1.79	3.54
Exchangeable K	cmol ⁺ kg ⁻¹	1.11	8.26
Exchangeable Na	cmol ⁺ kg ⁻¹	0.48	3.22
Water-extractable Zn	mg kg ⁻¹	< 0.25	5.42
Water-extractable Cu	mg kg ⁻¹	< 0.25	3.49
Water-extractable Mn	mg kg ⁻¹	< 0.2	4.65
Water-extractable Fe	mg kg ⁻¹	< 0.2	32.3
Water-extractable Mg	mg kg ⁻¹	191	132.6
Water-extractable K	mg kg ⁻¹	632.2	4823.0
Water-extractable Na	mg kg ⁻¹	120.4	1417
Total Zn	mg kg ⁻¹	12.1	187.6
Total Cu	mg kg ⁻¹	3.2	46.3
Total Mn	mg kg ⁻¹	463.8	431.3
Total Fe	mg kg ⁻¹	4028	4883
Total Ca	mg kg ⁻¹	6834	20986
Total Mg	mg kg ⁻¹	840	3551
Total K	mg kg ⁻¹	2878	23975
Total Na	mg kg ⁻¹	349	2510

2.3 Experimental design and treatments

The experiment was conducted in two adjacent areas: i) a flat site, and ii) a terraced site (a levelled bench created on a steep slope through soil tillage to reduce erosion and improve site conditions for planting). The field trial was arranged in three replicated blocks in each area. Six treatments were established in the flat area, with 15 plants per treatment distributed across the three blocks. Three treatments were established in the terraced area, with 12 plants per treatment distributed across the three blocks. The treatments were defined as follows: i) T0: control without NPK (fertiliser), ii) T0A: control with NPK, iii) T1: Biochar Pure without NPK, iv) T2: Biochar Pure with NPK, v) T3: Biochar Plus without NPK, and vi) T4: Biochar Plus with NPK.

In the terraced area, only T0A, T3 and T4 were implemented due to operational constraints. Biochar was applied locally within each planting hole at a volume of 1.2 L per plant, based on preliminary incubation trials targeting a soil pH range suitable for *E. globulus* establishment (approximately 6.0–6.5). Mineral fertilisation consisted of 30 g Agroblen (11-22-9 + 6% MgO; 8–9 month controlled-release fertiliser, ICL Speciality Fertilisers) and 60 g of triple calcium superphosphate (42% P₂O₅; ADP Fertilizantes) per plant, reflecting standard plantation practice.

Planting was carried out on 20 June 2016 using *Eucalyptus globulus* seedlings. Soil tillage included light harrowing and ripping before planting. At approximately 1,250 plants ha⁻¹, the local application corresponded to a nominal biochar volume of 1.5 m³ ha⁻¹. Because biochar was incorporated only within the planting holes rather than distributed uniformly across the site, this value should not be interpreted as a whole-field incorporation rate. Detailed treatment descriptions, application rates, and plant numbers are provided in Table S1 (Supplementary Information).

2.4 Soil sampling and analytical methods

Soil samples were collected before treatment application, at the first post-planting soil sampling approximately 5 months after planting, and at 12 months after planting. Sampling was conducted at 0–20 cm depth using composite samples consisting of at least ten subsamples per treatment and replicate. Laboratory analyses included: i) soil pH (ISO 10390, 2005), ii) organic matter (OM) and organic carbon (OC), iii) available phosphorus (P), iv) total nitrogen (N), v) exchangeable base cations (Ca, Mg, K, Na), vi) CEC, and vii) selected micronutrients (Zn, Cu, Mn, Fe, B). Organic carbon was estimated from organic matter using a standard conversion factor (OC% = OM% × 0.58). Elemental concentrations were determined using ICP-OES following standard extraction procedures (Verheijen et al., 2010).

2.5 Plant measurements

Plant survival was assessed one month after planting, and dead individuals were replaced to ensure uniform stand conditions. Tree height was measured for all available trees at 5 and 12 months after trial implementation. For statistical analysis, measurements were averaged within each treatment-by-block combination, and the three block-level means were treated as the experimental replicates (n = 3 per treatment). Treatment mean height was used as the primary indicator of early plantation performance. Visual differences in plant development across treatments are illustrated in Fig. 2. Plant survival, mean

height and relative changes are summarised in Table 3, and the detailed monitoring schedule is provided in Table S2 (Supplementary Information).

2.6 Statistical analysis

All statistical analyses were performed with SPSS v26. Differences among treatments were evaluated using analysis of variance (ANOVA), followed by Tukey's Honestly Significant Difference (HSD) test at a significance level of $p < 0.05$. Statistical analyses were performed separately for the flat and terraced areas due to differences in treatment structure and baseline conditions. Treatment effects were assessed for both plant height and soil chemical parameters. Relative changes in mean values for each dependent variable were calculated as:

$$\text{Relative change (\%)} = \left(\frac{\text{Mean treatment} - \text{Mean control}}{\text{Mean control}} \right) \times 100 \text{ (Eq. 1)}$$

2.7 Complementary indices

To support the interpretation of treatment effects, two complementary indices were developed based on absolute measured values.

2.7.1 Biochar–Fertiliser Synergy Index (BFSI)

The Biochar–Fertiliser Synergy Index (BFSI) was used to quantify whether the combined effect of biochar and mineral fertilisation exceeded the sum of their individual effects for a given variable X :

$$BFSI_X = \frac{X_{\text{Biochar+NPK}} - X_{\text{Control}}}{(X_{\text{Biochar_only}} - X_{\text{Control}}) + (X_{\text{NPK_only}} - X_{\text{Control}})} \text{ (Eq. 2)}$$

BFSI values greater than 1 indicate a supra-additive response, a value of 1 indicates an additive response, and values below 1 indicate a sub-additive response. The index was calculated descriptively from treatment means and was not used as a formal statistical interaction test.

BFSI was calculated for the flat area only, where a complete factorial structure was available. For T2, T1 was used as the biochar-only comparator, and for T4, T3 was used as the biochar-plus-only comparator, both relative to T0.

2.7.2 Forest Soil Quality Index (FSQI)

A Forest Soil Quality Index (FSQI) was developed as an exploratory composite indicator of soil chemical condition for *Eucalypt* establishment. Soil pH, organic carbon (OC), base saturation (BS), and available phosphorus (P) were selected because they represent complementary dimensions of soil fertility in acidic forest soils: soil acidity, carbon status, exchangeable-base status, and plant-available phosphorus, respectively. Equal weights of 0.25 were assigned to avoid prioritising any individual variable in the absence of an independently validated weighting scheme:

$$FSQI = 0.25 \times pH_{norm} + 0.25 \times OC_{norm} + 0.25 \times BS_{norm} + 0.25 \times P_{norm} \text{ (Eq. 3)}$$

Base saturation was calculated as:

$$BS = \frac{(Ca + Mg + K + Na)}{CEC \times 100} \text{ (Eq. 4)}$$

The individual indicators were transformed to a common 0–1 scale using the following operational reference bounds:

$$pH_{norm} = \frac{pH - 4.5}{7.0 - 4.5}; OC_{norm} = \frac{OC}{10}; BS_{norm} = \frac{BS}{50}; P_{norm} = \frac{P}{25} \text{ (Eq. 5)}$$

where OC and BS are expressed as percentages and P as mg kg⁻¹. Normalised values below 0 were assigned a value of 0, and values exceeding 1 were capped at 1. The bounds represent operational scoring thresholds used to compare treatments and should not be interpreted as independently validated critical values for *Eucalyptus globulus*. The FSQI was therefore used as a complementary interpretative index rather than as a primary statistical endpoint.

2.7.3 Integrated *Eucalypt* Growth Index (IEGI)

To link soil condition with plant performance, an Integrated *Eucalypt* Growth Index (IEGI) was calculated as:

$$IEGI = \left(\frac{H_{treatment}}{H_{control}} \right) \times FSQI \text{ (Eq. 6)}$$

Where $H_{treatment}$ and $H_{control}$ represent the mean plant height for each treatment and the corresponding area-specific control, respectively. These indices were used as complementary indicators to support the interpretation of treatment effects rather than as primary statistical outputs.

3. Results

3.1 *Eucalypt* growth response

Initial survival one month after planting was high across treatments. In the flat area, survival was 87% in T0, 93% in T0A and T1, and 100% in T2, T3 and T4. In the terraced area, survival was 100% in T0A, 92% in T3 and 100% in T4. Dead seedlings were subsequently replaced as described in Section 2.5; therefore, survival was not analysed as a later treatment response.

At 5 months after planting, plant height differed significantly among treatments in the flat area (Fig. 3 and Table 3). The control without fertilisation (T0) reached 0.7 m, while mineral fertilisation alone (T0A) increased plant height to 1.1 m (+ 57%). Biochar without fertilisation (T1) showed no effect relative to the control (0.7 m), whereas Biochar Plus without fertilisation (T3) increased plant height to 0.9 m (+ 29%). The highest values were observed in treatments combining biochar and fertilisation, with 1.3 m in both T2 and T4 (+ 86%). In the terraced area, where only T0A, T3 and T4 were established, plant height at 5

months was 1.09 m in T0A, 1.05 m in T3 (– 4%) and 1.18 m in T4 (+ 8%) relative to the fertilised control, with no statistically significant differences among treatments. At 12 months, treatment effects were more pronounced.

In the flat area, plant height remained 1.2 m in both T0 and T1. Fertilised treatments showed significantly higher values, with 2.6 m in T0A (+ 117%), 3.3 m in T2 (+ 175%), and 3.1 m in T4 (+ 158%). Biochar Plus without fertilisation (T3) reached 2.1 m (+ 75%). Although its mean height was lower than that of fertilisation alone (T0A; 2.6 m), the two treatments were not statistically different. In the terraced area, plant height was 2.77 m in T0A, 2.34 m in T3 (– 15%), and 3.26 m in T4 (+ 18%) relative to the fertilised control. At this stage, T4 was significantly higher than both T0A and T3.

Similarly, T3 and T0A did not differ significantly in the terraced area at either sampling time, although T3 showed lower mean height at 12 months. Treatment means, significance groupings and relative changes are summarised in Table 3. For treatments present in both areas, plant height was generally higher in the terraced area than in the flat area at 5 and 12 months. Because the two areas did not include the same full treatment structure, this pattern is reported descriptively.

Table 3

Initial plant survival and mean height of *Eucalyptus globulus* at 5 and 12 months after planting. Relative changes were calculated against the area-specific control: T0 for the flat area and T0A for the terraced area. Different lowercase letters within the same area and sampling time indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$).

Area	Treatment	Survival (%)	Height at 5 months (m)	Relative change (%)	Height at 12 months (m)	Relative change (%)
Flat	T0 – Control without NPK	87	0.70 c	–	1.20 d	–
Flat	T0A – Control with NPK	93	1.10 ab	57.1	2.60 bc	116.7
Flat	T1 – Biochar Pure without NPK	93	0.70 c	0	1.20 d	0
Flat	T2 – Biochar Pure with NPK	100	1.30 a	85.7	3.30 a	175
Flat	T3 – Biochar Plus without NPK	100	0.90 bc	28.6	2.10 c	75
Flat	T4 – Biochar Plus with NPK	100	1.30 a	85.7	3.10 ab	158.3
Terrace	T0A – Control with NPK	100	1.09 a	–	2.77 b	–
Terrace	T3 – Biochar Plus without NPK	92	1.05 a	-3.7	2.34 b	-15.5
Terrace	T4 – Biochar Plus with NPK	100	1.18 a	8.3	3.26 a	17.7

3.2 Temporal changes in soil chemical properties

Soil chemical properties responded strongly to biochar application at the first post-planting soil sampling approximately 5 months after planting, but several effects weakened by 12 months (Table 4). Complete soil chemical results and statistical groupings are provided in Table S6. In the flat area, soil pH increased from the initial value of 5.2 to 5.5–5.8 in biochar-amended treatments at the first sampling, with the highest value in T3. In contrast, fertilisation alone decreased pH to 4.9. By 12 months, the liming effect was less evident, with pH ranging from 4.8 to 5.4 in biochar-amended treatments and no consistent separation between biochar and non-biochar treatments.

Organic matter and organic carbon showed more persistent responses. In the flat area, organic matter increased from 6.5% initially to 10.5% in T1, 9.2% in T2, and 8.0–8.5% in T3–T4 at the first sampling. At 12 months, organic carbon remained elevated in biochar-amended treatments, reaching 5.51% in T1 and

5.74% in T2 compared with 4.00% in T0. In the terraced area, organic matter increased from 10.3% initially to 18.5% in T3 and 16.0% in T4 at the first sampling, while organic carbon remained high at 12 months, reaching 9.11% in T3 and 10.03% in T4.

Available phosphorus increased markedly in fertilised treatments. In the flat area, P increased from 6.6 mg kg⁻¹ initially to 33.6 mg kg⁻¹ in T0A and 44.8 mg kg⁻¹ in T4 at the first sampling, while remaining low in T1. At 12 months, P remained elevated in fertilised treatments, reaching 50.5 mg kg⁻¹ in T0A, 47.7 mg kg⁻¹ in T2, and 36.4 mg kg⁻¹ in T4. In the terraced area, P increased from 7.9 mg kg⁻¹ initially to 104.8 mg kg⁻¹ in T3 and 156.2 mg kg⁻¹ in T4 at the first sampling and remained highest in T4 at 12 months (125.8 mg kg⁻¹).

Exchangeable bases and CEC showed the strongest short-term responses in Biochar Plus treatments. In the flat area, T3 and T4 showed higher exchangeable Ca, Mg, K, Na and CEC than the control at the first sampling, indicating a broad enrichment of the exchangeable nutrient pool rather than an isolated Ca response.

CEC increased from 3.1 cmolc kg⁻¹ initially to 6.2 cmolc kg⁻¹ in T3 and 5.6 cmolc kg⁻¹ in T4. In the terraced area, where baseline fertility and clay content were higher, the response was also pronounced, with CEC increasing from 5.1 cmolc kg⁻¹ initially to 10.6 cmolc kg⁻¹ in T3 and 10.5 cmolc kg⁻¹ in T4. By 12 months, these short-term increases had declined, with CEC decreasing to 3.29–3.39 cmolc kg⁻¹ in T3–T4 in the flat area and to 5.87–6.61 cmolc kg⁻¹ in T3–T4 in the terraced area. Key treatment means are summarised in Table 4, while relative changes and the complete soil chemical dataset are provided in Tables S3 and S6, respectively.

Table 4

Selected soil chemical properties at approximately 5 and 12 months after planting in the flat and terraced areas. Values are treatment means. Initial 0–20 cm values were pH 5.2, OC 3.77%, P 6.6 mg kg⁻¹ and CEC 3.10 cmolc kg⁻¹ in the flat area, and pH 4.9, OC 5.97%, P 7.9 mg kg⁻¹ and CEC 5.10 cmolc kg⁻¹ in the terraced area. Complete soil chemical data and statistical groupings are provided in Table S6.

Panel A. Soil pH and organic carbon

Area	Treatment	pH, 5 months	pH, 12 months	OC (%), 5 months	OC (%), 12 months
Flat	T0 – Control without NPK	5.2	4.9	3.89	4
Flat	T0A – Control with NPK	4.9	4.7	4.06	3.94
Flat	T1 – Biochar Pure without NPK	5.5	5.4	6.09	5.51
Flat	T2 – Biochar Pure with NPK	5.5	5	5.34	5.74
Flat	T3 – Biochar Plus without NPK	5.8	5.1	4.64	5.34
Flat	T4 – Biochar Plus with NPK	5.5	4.8	4.93	4.41
Terrace	T0A – Control with NPK	5	4.7	6.55	5.86
Terrace	T3 – Biochar Plus without NPK	5.8	5	10.73	9.11
Terrace	T4 – Biochar Plus with NPK	5.4	4.7	9.28	10.03

Panel B. Available phosphorus and cation exchange capacity

Area	Treatment	P (mg kg ⁻¹), 5 months	P (mg kg ⁻¹), 12 months	CEC (cmolc kg ⁻¹), 5 months	CEC (cmolc kg ⁻¹), 12 months
Flat	T0 – Control without NPK	6.4	11.5	3.2	3.05
Flat	T0A – Control with NPK	33.6	50.5	3.8	3.83
Flat	T1 – Biochar Pure without NPK	4.4	16.3	3.7	2.92
Flat	T2 – Biochar Pure with NPK	21.3	47.7	3.4	3.06
Flat	T3 – Biochar Plus without NPK	22	20.4	6.2	3.29
Flat	T4 – Biochar Plus with NPK	44.8	36.4	5.6	3.39
Terrace	T0A – Control with NPK	36.1	36.5	5.9	5.49
Terrace	T3 – Biochar Plus without NPK	104.8	32.1	10.6	5.87
Terrace	T4 – Biochar Plus with NPK	156.2	125.8	10.5	6.61

3.3 Biochar–Fertiliser Synergy Index (BFSI)

The Biochar–Fertiliser Synergy Index (BFSI) was calculated for plant height in the flat area to quantify whether the combined application of biochar and mineral fertilisation produced a response greater than the sum of their individual effects. At 5 months, BFSI was 1.50 for T2 and 1.00 for T4. At 12 months, BFSI remained 1.50 for T2 but decreased to 0.83 for T4. These values indicate that the combination of pure biochar and mineral fertilisation produced a consistently supra-additive response.

In contrast, the response of Biochar Plus combined with fertilisation was additive at 5 months and sub-additive at 12 months. The lower BFSI value for T4 at 12 months reflects the comparatively strong standalone effect of Biochar Plus on plant growth, which reduced the relative interaction term when combined with mineral fertilisation.

3.4 Forest Soil Quality Index (FSQI) and Integrated *Eucalypt* Growth Index (IEGI)

The relationship between soil quality and plant performance is illustrated in Fig. 4, while the complete FSQI and IEGI values are presented in Table 5. In the flat area, FSQI ranged from 0.352 in T0 to 0.598 in T1, whereas IEGI ranged from 0.352 in T0 to 1.525 in T2. In the terraced area, the highest FSQI occurred in T4 (0.770), while the highest IEGI also occurred in T4 (0.906).

The different treatment rankings produced by FSQI and IEGI show that improved soil chemical condition did not necessarily translate into greater plant growth. Biochar Pure alone produced a relatively high FSQI but no growth response, whereas the combined biochar–fertiliser treatments produced the highest IEGI values within each area. Thus, soil improvement translated most strongly into early plant performance when accompanied by adequate nutrient supply.

Table 5
Forest Soil Quality Index (FSQI) and Integrated Eucalypt Growth Index (IEGI) at 12 months after planting. FSQI integrates normalised soil pH, organic carbon, base saturation and available phosphorus, while IEGI combines FSQI with relative plant height.

Area	Treatment	FSQI	IEGI
Flat	T0 – Control without NPK	0.352	0.352
Flat	T0A – Control with NPK	0.502	1.087
Flat	T1 – Biochar Pure without NPK	0.598	0.598
Flat	T2 – Biochar Pure with NPK	0.555	1.525
Flat	T3 – Biochar Plus without NPK	0.56	0.98
Flat	T4 – Biochar Plus with NPK	0.502	1.298
Terrace	T0A – Control with NPK	0.576	0.576
Terrace	T3 – Biochar Plus without NPK	0.762	0.644
Terrace	T4 – Biochar Plus with NPK	0.77	0.906

4. Discussion

4.1 Biochar-induced changes in soil chemical properties

Biochar application produced rapid and substantial changes in soil chemical properties, particularly within the first 5 months, which mostly had disappeared by 12 months. Soil pH increased from 5.2 to 5.5–5.8, corresponding to a rise of + 0.3 to + 0.6 units, consistent with the liming effect of biochar reported in acidic soils (Glaser et al., 2002; Spokas et al., 2012; Lehmann and Joseph, 2015). Similar magnitudes of pH increase (typically + 0.2 to + 1.0 units) have been widely reported across field and meta-analytical studies, particularly in strongly acidic systems (Borchard et al., 2014; Schmidt et al., 2021).

By 12 months, the initial liming effect of biochar was substantially reduced and no longer statistically significant. This contrasts with meta-analytical evidence suggesting that biochar-induced increases in soil pH can persist for several years under many conditions (Zhang et al., 2025). In the present field trial, the attenuation of the liming effect may partly reflect leaching, redistribution, or plant uptake of soluble

alkaline components during the wet season between the first and second soil samplings, particularly given the coarse-textured and well-drained nature of the flat-area soil and the humid Mediterranean conditions of the study site.

This interpretation is consistent with the decline in exchangeable base cations and CEC between the first and second samplings, especially in Biochar Plus treatments. However, because soil moisture, drainage, infiltration, and leachate chemistry were not measured, this explanation remains tentative. Organic matter increased by up to + 62% (T1) and remained elevated at 12 months (+ 46–52% in T1–T2), indicating persistence of biochar-derived carbon. These values fall within the upper range reported in field studies, where increases in soil carbon content typically range from + 10% to + 50% depending on application rate and soil type (Jeffery et al., 2011; Agegnehu et al., 2017).

The relatively strong response may reflect the localised application of 1.2 L biochar within the sampled planting zone, together with the comparatively low initial soil organic carbon concentration. The substantial increase in soil organic carbon concentration, particularly in the terraced area (+ 55–71%), indicates greater carbon concentration within the sampled planting zone at 12 months. Notably, Biochar Plus produced similar or higher organic carbon concentrations despite its lower initial carbon content (61% versus 78%), suggesting that the observed response was not determined solely by the carbon concentration of the applied product. It may also reflect differences in biochar composition, local soil conditions and indirect soil–plant processes. However, because soil bulk density, treatment-scale carbon stocks, and complete carbon inputs and losses were not quantified, these results should not be interpreted as direct evidence of stand-scale carbon-stock gains, net carbon removal or carbon-removal permanence (Gholamahmadi and Kammann, 2026). Dedicated carbon-stock and long-term monitoring would be required to evaluate these outcomes.

Exchangeable base cations and CEC showed strong short-term responses to Biochar Plus application. This response was not limited to Ca, but was also reflected in higher Mg, K, Na and CEC at the first soil sampling, indicating a broader enrichment of the exchangeable nutrient pool. The response was particularly clear in the terraced area, where CEC increased from 5.1 cmolc kg⁻¹ initially to 10.6 and 10.5 cmolc kg⁻¹ in T3 and T4, respectively. By 12 months, these increases were substantially reduced, suggesting depletion, redistribution or plant uptake of exchangeable bases over time.

These results are consistent with the role of mineral-enriched biochar in temporarily increasing nutrient availability and exchange capacity, while also highlighting the importance of biochar composition and site conditions in controlling the persistence of these effects (Singh et al., 2010; Sohi et al., 2010; Lehmann and Joseph, 2015; Gholamahmadi, 2026b). Available P increased from 6.6 mg kg⁻¹ to 44.8 mg kg⁻¹ (+ 579%) in T4 and up to 156.2 mg kg⁻¹ in the terraced area (~ 20-fold increase). While much of this increase is attributable to fertilisation, the higher values in combined treatments relative to fertilisation alone indicate enhanced retention or reduced sorption effects.

Similar synergistic effects between biochar and fertiliser P availability have been reported, particularly in acidic soils where biochar can reduce P sorption and improve availability (Chan et al., 2008; Van Zwieten

et al., 2010; Prodana et al., 2021). The reduction in effect magnitude at 12 months suggests partial stabilisation of the system, consistent with previous field studies showing that early increases in nutrient availability and exchange capacity tend to decline or stabilise over time due to plant uptake, leaching, and redistribution processes (Major et al., 2010; Idbella et al., 2024).

4.2 Growth response and fertilisation efficiency

Despite substantial improvements in soil chemical properties, biochar alone (T1) did not increase plant height relative to the control (both 1.2 m at 12 months), indicating that improved soil conditions did not translate into increased growth in the absence of nutrient supply. It should be noted that although biochar raised the soil pH from 5.2 to 5.5, which is associated with a substantial decrease in soluble Al, *E. globulus* is particularly tolerant to Al^{3+} (Gomes et al., 2019).

The lack of effects on plant height is consistent with meta-analyses showing that biochar effects on plant productivity are often negligible in the absence of fertilisation, particularly in nutrient-limited systems (Jeffery et al., 2011; Biederman and Harpole, 2013; Thomas and Gale, 2015; Yang et al., 2025). In contrast, mineral fertilisation increased plant height by +117% (T0A), confirming that nutrient limitation was the primary constraint to early growth. Relative to the unfertilised control, T2 and T4 increased plant height by 175% and 158%, respectively. When compared directly with fertilisation alone, T2 and T4 increased plant height by 27% and 19%, respectively, at 12 months. These treatment contrasts support a complementary effect of biochar on fertiliser performance, although comparisons with published biochar–fertiliser interaction effects require the same reference treatment and experimental context (Chan et al., 2008; Van Zwieten et al., 2010; Ye et al., 2016; Agegnehu et al., 2017).

This interpretation is consistent with recent lysimeter studies in Mediterranean vineyard soil of sandy loam texture, where woody biochar increased vegetation cover by 263%, raised soil pH to near-neutral conditions (6.81), and improved nutrient availability, including plant-available P (+43.5%), K (+162.3%), and mineral N forms (Gholamahmadi et al., 2025a). The BFSI values further quantify this interaction. A value of 1.50 in T2 indicates a supra-additive effect, meaning that the combined response exceeded the sum of individual contributions.

This supports the hypothesis that biochar enhances fertilisation efficiency, likely through improved nutrient retention and reduced losses. In contrast, the lower BFSI in T4 (0.83) reflects a different interaction pattern, where the strong standalone effect of Biochar Plus (T3: +75%) reduces the relative interaction term. These findings are consistent with recent studies showing that biochar can enhance nutrient use efficiency rather than act as a direct fertiliser, particularly in early-stage systems where nutrient demand is high (Ali et al., 2025; Yang et al., 2025).

The comparison between Biochar Plus without NPK (T3) and fertilisation alone (T0A) provides partial support for H4. In both areas, T3 was not statistically different from T0A, although its mean plant height at 12 months was lower. This indicates that the mineral-enriched biochar supplied part of the functional benefit associated with conventional fertilisation but did not fully reproduce the growth response

obtained from mineral nutrient application. Moreover, the highest growth was obtained when Biochar Plus was combined with NPK, confirming that its principal value was as a nutrient-enriched complementary bioproduct rather than as a complete fertiliser substitute.

4.3 Soil–plant coupling and functional response (FSQI and IEGI)

The combined analysis of soil and plant responses provides further insight into treatment performance. FSQI values were highest in biochar-amended treatments, reaching 0.762–0.770 in the terraced area (T3–T4), compared to 0.352 in the control, reflecting substantial improvements in soil chemical condition. However, these improvements did not translate proportionally into plant growth. For example, T1 showed a relatively high FSQI (0.598), but no increase in plant height, resulting in a moderate IEGI (0.598). This decoupling between soil quality and plant growth highlights that soil improvement alone is insufficient to overcome nutrient limitations during early establishment.

In contrast, treatments combining biochar and fertilisation achieved the highest IEGI values, reaching 1.525 in T2 (flat) and 0.906 in T4 (terraced). These values reflect both enhanced soil condition and increased plant growth, indicating a functional coupling between soil improvement and plant response. The divergence between FSQI and IEGI across treatments demonstrates that soil chemical indicators alone may overestimate functional outcomes, and that integrated indices provide a more realistic assessment of system performance (Prodana et al., 2021). This is particularly relevant in forest systems, where early growth depends on both soil condition and nutrient availability (Thomas and Gale, 2015; Antonangelo et al., 2025).

4.4 Implications for circular forest bioresource management and sustainability

The results demonstrate that biochar can substantially improve soil chemical properties in acidic forest soils, but its effect on plant growth depends strongly on nutrient availability. The combined application of biochar and fertilisation produced the highest growth responses, indicating improved fertilisation efficiency. From a management perspective, these findings suggest that biochar should be considered as a complementary amendment rather than a substitute for fertilisation during plantation establishment. The observed increases in CEC, base cations and P availability indicate that biochar can enhance nutrient retention and potentially reduce fertiliser losses over time.

In the context of forest-based bioresource systems, the present study provides a practical example of converting *Eucalyptus* biomass residues into a functional biochar bioproduct and returning it to *Eucalyptus* plantation soils, consistent with emerging strategies for valorising waste lignocellulosic biomass into soil-restorative products within a circular bioeconomy (Shakeel et al., 2026).

This creates a circular fibre-production pathway in which residues from the forest sector are valorised into a stable carbon-rich amendment that supports soil regeneration, nutrient retention and early stand

establishment. Such a pathway is directly relevant to pulp- and paper-oriented plantation systems, where maintaining soil fertility and improving fertiliser-use efficiency are central to long-term resource productivity. In addition, the carbon stored through biochar application may create future opportunities for landowners or forest managers to access carbon sequestration credits if biochar production, application, monitoring and permanence are verified under recognised certification frameworks (Gholamahmadi et al., 2026b).

This approach aligns with emerging circular forestry strategies in which residues are valorised into stable carbon-rich amendments that improve soil condition, reduce waste streams and lower dependency on external inputs (Bruckman and Pumpanen, 2019; Wrobel-Tobiszewska et al., 2015; Homagain et al., 2016; Bastos et al., 2025; Pérez et al., 2025; Biswal and Balasubramanian, 2025). Under this framework, the observed improvements in soil condition and early plant establishment contribute directly to forest productivity, resource efficiency and ecosystem functioning, reinforcing the role of biochar as a practical bridge between circular bioresource use, functional bioproduct development and sustainable forest management (Thomas and Gale, 2015; Gholamahmadi et al., 2026a).

4.5 Limitations and outlook

Biochar was applied locally within the planting holes rather than incorporated uniformly across the plantation soil. This targeted application reduced the amount of material required but likely restricted its influence to the immediate root zone and limits extrapolation of the observed responses to the stand scale. The study also did not include an economic assessment. Although localised application may be more operationally feasible than whole-area incorporation, the costs of biochar production, transport and field application may constrain adoption in commercial forestry. Evidence extending across complete forest rotation cycles remains limited; therefore, it is not yet possible to determine whether improvements in stand productivity, nutrient-use efficiency, carbon storage or other ecosystem services would compensate for the initial investment at commercial scale (Homagain et al., 2016; Antonangelo et al., 2025).

The present study focuses on soil chemical properties and early plant growth during the first 12 months after plantation establishment. While clear treatment effects were observed, an important limitation is the absence of measurements related to soil physical and hydrological properties. Variables such as soil water storage and moisture dynamics were not assessed, despite their known relevance in mediating plant responses to biochar amendments (Blanco-Canqui, 2017; Razzaghi et al., 2020).

This limitation is significant given that biochar has been widely reported to influence soil water retention, infiltration capacity and runoff, especially in coarser-textured, structurally limited soils (Gholamahmadi et al., 2023, 2025b). The lack of hydrological measurements restricts the ability to fully interpret the mechanisms underlying the observed growth responses, particularly under Mediterranean conditions, where water availability is a key limiting factor.

Future research should integrate soil hydrological measurements with chemical and biological indicators, including long-term monitoring of potentially relevant trace elements (Chandra et al., 2022). Such studies should quantify soil water storage, infiltration and plant-available water, track nutrient dynamics and tree growth across a complete plantation rotation, and include techno-economic assessment to determine whether gains in productivity, resource-use efficiency, carbon storage and ecosystem services can offset the initial cost of biochar deployment.

5. Conclusions

This study provides field-based evidence that biochar can substantially modify soil chemical conditions during early *E. globulus* plantation establishment, but that its effect on plant growth depends strongly on mineral nutrient availability and site conditions. Biochar increased soil pH by + 0.3 to + 0.6 units, organic matter by + 23–62%, and CEC by + 81–108% at the first post-planting soil sampling, although the liming effect was no longer statistically significant at 12 months. These responses confirm that biochar can rapidly improve soil chemical status in acidic Mediterranean forest soils, particularly when mineral-enriched biochar is applied.

However, soil improvement alone was insufficient to increase early tree growth when Pure biochar was applied without NPK. Mineral-enriched Biochar Plus produced a moderate standalone growth response and partially approached the response obtained with mineral fertilisation, providing partial support for its capacity to substitute conventional fertilisation during early establishment. Nevertheless, mineral fertilisation remained the dominant driver of growth, increasing plant height by + 57% at 5 months and + 117% at 12 months. The strongest responses occurred when biochar was combined with NPK, reaching + 175% in T2 and + 158% in T4 at 12 months. The Biochar–Fertiliser Synergy Index further indicated a supra-additive response for Pure biochar combined with NPK (BFSI = 1.50), showing that the principal value of biochar was to enhance fertilisation efficiency rather than fully replace mineral fertilisation.

The comparison between flat and terraced areas further showed that biochar performance was site-dependent. The terraced area had higher baseline organic matter, clay content, CEC and base saturation, whereas the flat area showed clearer relative growth responses to combined biochar–fertiliser treatments. Integrated FSQI and IEGI values confirmed that improvements in soil condition translated into stronger plant performance only when coupled with nutrient supply.

Overall, biochar should be considered a functional forest bioproduct for Mediterranean *E. globulus* plantations. Under the conditions of this study, biochar did not fully replace mineral fertilisation during early establishment, but improved soil condition, enhanced fertiliser performance and contributed to more integrated soil–plant system responses. These findings support the use of forest-residue-derived biochar in circular fibre-production systems aimed at improving nutrient-use efficiency, soil quality, carbon retention and early plantation performance.

Declarations

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

Author Contribution

B.G.: Investigation, Formal analysis, Validation, Visualisation, Writing – original draft, Writing – review and editing. F.G.A.V.: Conceptualisation, Investigation, Methodology, Formal analysis, Writing – review and editing. S.F.: Conceptualisation, Methodology, Investigation, Resources, Writing – review and editing. A.Q.: Conceptualisation, Investigation, Methodology, Data curation, Formal analysis, Supervision, Writing – review and editing. All authors read and approved the final manuscript.

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Data Availability

The data analysed during the current study are available from the corresponding author upon reasonable request.

References

1. Agegnehu, G., Srivastava, A. K., and Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Agriculture, Ecosystems and Environment*, 236, 1–15. <https://doi.org/10.1016/j.agee.2016.12.024>
2. Ali, A., Jabeen, N., Chachar, Z., Chachar, S., Ahmed, S., Ahmed, N., Laghari, A. A., Sahito, Z. A., Farruhbek, R., and Yang, Z. (2025). The role of biochar in enhancing soil health & interactions with rhizosphere properties and enzyme activities in organic fertilizer substitution. *Frontiers in Plant Science*, 16, 1595208. <https://doi.org/10.3389/fpls.2025.1595208>
3. Antonangelo, J.A., Sun, X., Eufrade-Junior, H.J., 2025. Biochar impact on soil health and tree-based crops: a review. *Biochar* 7, 51. <https://doi.org/10.1007/s42773-025-00450-6>
4. Asif, A.H., Shi, L., Ding, T., Zhang, S., Sun, H., 2025. Emerging engineered biochar for environmental and energy applications. *J. Bioresour. Bioprod.* 10, 1–3. <https://doi.org/10.1016/j.jobab.2024.11.004>
5. Bastos, T., Nunes, L. J. R., and Teixeira, L. (2025). Fostering circularity in agroforestry biomass: A regulatory framework for sustainable resource management. *Land*, 14(2), 362. <https://doi.org/10.3390/land14020362>

6. Biederman, L. A., and Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy*, 5(2), 202–214. <https://doi.org/10.1111/gcbb.12037>
7. Biswal, B.K., Balasubramanian, R., 2025. Use of biomass-derived biochar as a sustainable material for carbon sequestration in soil: recent advancements and future perspectives. *npj Mater. Sustain.* 3, 26. <https://doi.org/10.1038/s44296-025-00066-8>
8. Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal*, 81(4), 687–711. <https://doi.org/10.2136/sssaj2017.01.0017>
9. Borchard, N., Wolf, A., Laabs, V., Ahrens, B., and Scherer, H. W. (2014). Biochar, soil organic matter and soil fertility – A review. *Journal of Plant Nutrition and Soil Science*, 177(5), 739–748. <https://doi.org/10.1002/jpln.201400047>
10. Bruckman, V. J., and Pumpanen, J. (2019). Biochar use in global forests: Opportunities and challenges. In M. Busse, C. P. Giardina, D. M. Morris, and D. S. Page-Dumroese (Eds.), *Developments in soil science: Vol. 36. Global change and forest soils* (pp. 427–453). Elsevier. <https://doi.org/10.1016/B978-0-444-63998-1.00017-3>
11. Bruckman, V. J., Terada, T., & Uzun, B. B. (2016). Biochar for climate change mitigation and adaptation in European forestry. In V. J. Bruckman, E. Apaydin Varol, B. B. Uzun, & J. Liu (Eds.), *Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation* (pp. 145–168). Cambridge University Press.
12. Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., and Joseph, S. (2008). Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*, 46(5), 437–444. <https://doi.org/10.1071/SR08036>
13. Chandra, S., Medha, I., Bhattacharya, J., Vanapalli, K. R., and Samal, B. (2022). Effect of the Co-Application of Eucalyptus Wood Biochar and Chemical Fertilizer for the Remediation of Multimetal (Cr, Zn, Ni, and Co) Contaminated Soil. *Sustainability*, 14(12), 7266. <https://doi.org/10.3390/su14127266>
14. Fabres, S., Ferreira, D., Silva, P., & Meireles, E. (2005). Indicadores da fertilidade do solo e do estado nutricional da planta para o cultivo de *Eucalyptus globulus* [Relatório interno]. RAIZ – Instituto de Investigação da Floresta e Papel.
15. Gholamahmadi, B., Jeffery, S., Gonzalez-Pelayo, O., Prats, S.A., Bastos, A.C., Keizer, J.J., Verheijen, F.G.A. (2023). Biochar impacts on runoff and soil erosion by water: a systematic global-scale meta-analysis. *Sci. Total Environ.* 871, 161860. <https://doi.org/10.1016/j.scitotenv.2023.161860>
16. Gholamahmadi, B. (2026a). Biochar enhances soil hydrological buffering under hydroclimatic whiplash. *Water Science*. 40, 58. <https://doi.org/10.1007/s44533-026-00054-4>
17. Gholamahmadi, B. (2026b). Understanding feedstock-dependent biochar performance beyond static material descriptors. *Biochar X* 2, e016. <https://doi.org/10.48130/bchax-0026-0014>
18. Gholamahmadi, B., Gonzalez Pelayo, O., Isaka, S., Campos, I., Martins, M., Bastos, A. C., Jongen, M., and Verheijen, F. G. A. (2025a). The impact of biochar application on sponge function, water erosion,

- and vegetation cover in a Mediterranean vineyard soil. *Journal of Environmental Management*, 388, 125916. <https://doi.org/10.1016/j.jenvman.2025.125916>
19. Gholamahmadi, B., Ferreira, C.S.S., Gonzalez-Pelayo, O., Bastos, A.C., Verheijen, F.G.A. (2025b). Soil conservation benefits of biochar in Mediterranean vineyards: enhancing the soil sponge function and mitigating water erosion. *Biochar* 7, 106. <https://doi.org/10.1007/s42773-025-00483-x>
 20. Gholamahmadi, B., Fernandes, S., Correia, P., Couto, J., Jorge, R., and Oliveira, T. A. C. (2026a). Pilot-scale slow pyrolysis of residual and invasive biomass produces feedstock-dependent biochar properties. *Next Sustainability*, 8, 100424. <https://doi.org/10.1016/j.nxsust.2026.100424>
 21. Gholamahmadi, B., Štrubelj, L., and Ghaleigh, N. S. (2026b). Alignment between product-based regulation and soil process-based functions in biochar systems under EU policy. *Soil Advances*. 5, 100122, <https://doi.org/10.1016/j.soilad.2026.100122>
 22. Gholamahmadi, B., & Kammann, C. (2026). Biochar for durable carbon removal: Soil erosion reduction as a key mechanism. *Biomass Futures*. 1, 100020. <https://doi.org/10.1016/j.bmf.2026.100020>
 23. Glaser, B., Lehmann, J., and Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – A review. *Biology and Fertility of Soils*, 35(4), 219–230. <https://doi.org/10.1007/s00374-002-0466-4>
 24. Gomes, S. D. S., Gonçalves, J. L. D. M., Rocha, J. H. T., and Menegale, M. L. D. C. (2019). Tolerance of Eucalyptus and Pinus seedlings to exchangeable Aluminium. *Scientia Agricola*, 76(6), 494–500. <https://doi.org/10.1590/1678-992X-2018-0011>
 25. Homagain, K., Shahi, C., Luckai, N., and Sharma, M. (2016). Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. *Forest Ecosystems*, 3, Article 21. <https://doi.org/10.1186/s40663-016-0081-8>
 26. Idbella, M., Baronti, S., Giagnoni, L., Renella, G., Becagli, M., Cardelli, R., Maienza, A., Vaccari, F.P., Bonanomi, G., 2024. Long-term effects of biochar on soil chemistry, biochemistry, and microbiota: results from a 10-year field vineyard experiment. *Appl. Soil Ecol.* 195, 105217. <https://doi.org/10.1016/j.apsoil.2023.105217>
 27. ISO 10390. (2005). Soil quality – Determination of pH. International Organization for Standardization.
 28. Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., van Groenigen, J.W., Hungate, B.A., Verheijen, F.G.A., 2017. Biochar boosts tropical but not temperate crop yields. *Environ. Res. Lett.* 12, 053001. <https://doi.org/10.1088/1748-9326/aa67bd>
 29. Jeffery, S., Verheijen, F. G. A., van der Velde, M., and Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems and Environment*, 144(1), 175–187. <https://doi.org/10.1016/j.agee.2011.08.015>
 30. Khan, S., Irshad, S., Mehmood, K., Hasnain, Z., Nawaz, M., Rais, A., Gul, S., Wahid, M.A., Hashem, A., Abd_Allah, E.F., Ibrar, D., 2024. Biochar production and characteristics, its impacts on soil health,

- crop production, and yield enhancement: a review. *Plants* 13, 166.
<https://doi.org/10.3390/plants13020166>
31. Krull, E. S., Baldock, J. A., and Skjemstad, J. O. (2003). Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. *Functional Plant Biology*, 30(2), 207–222. <https://doi.org/10.1071/FP02085>
 32. Lehmann, J., and Joseph, S. (Eds.). (2015). *Biochar for environmental management: Science, technology and implementation* (2nd ed.). Routledge.
 33. Lehmann, J., Gaunt, J., and Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – A review. *Mitigation and Adaptation Strategies for Global Change*, 11(2), 395–419.
<https://doi.org/10.1007/s11027-005-9006-5>
 34. Madeira, M., Fabião, A., and Carneiro, M. (2012). Do harrowing and fertilisation at middle rotation improve tree growth and site quality in *Eucalyptus globulus* Labill. plantations in Mediterranean conditions? *European Journal of Forest Research*, 131(3), 583–596.
<https://doi.org/10.1007/s10342-011-0533-1>
 35. Major, J., Rondon, M., Molina, D., Riha, S. J., and Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*, 333(1–2), 117–128.
<https://doi.org/10.1007/s11104-010-0327-0>
 36. Mncedi, S., Görgens, J. F., Swanepoel, P. A., and Hardie, A. G. (2024). Effects of eucalypt and black wattle biochars from vacuum pyrolysis on sandy soil quality and cauliflower yield. *South African Journal of Plant and Soil*, 41, 110–122. <https://doi.org/10.1080/02571862.2024.2425639>
 37. Nguyen, B. T., Lehmann, J., Kinyangi, J., Smernik, R., Riha, S. J., and Engelhard, M. H. (2009). Long-term black carbon dynamics in cultivated soil. *Biogeochemistry*, 92(1–2), 163–176.
<https://doi.org/10.1007/s10533-008-9243-2>
 38. Pérez, S., Fernandez-Ferreras, J., Fernandez, I., Pérez, L., 2025. Estimating biochar yield per hectare from logging residues in *Eucalyptus globulus* stands. *Ind. Crops Prod.* 230, 121098.
<https://doi.org/10.1016/j.indcrop.2025.121098>
 39. Prodana, M., Bastos, A. C., Silva, A. R. R., Morgado, R. G., Frankenbach, S., Serôdio, J., Soares, A. M. V. M., and Loureiro, S. (2021). Soil functional assessment under biochar, organic amendments and fertilizers applications in small-scale terrestrial ecosystem models. *Applied Soil Ecology*, 168, 104157. <https://doi.org/10.1016/j.apsoil.2021.104157>
 40. Razzaghi, F., Obour, P. B., and Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, 361, Article 114055.
<https://doi.org/10.1016/j.geoderma.2019.114055>
 41. Schmidt, H.P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T. D., Sánchez Monedero, M. A., and Cayuela, M. L. (2021). Biochar in agriculture – A systematic review of 26 global meta-analyses. *GCB Bioenergy*, 13, 1708–1730. <https://doi.org/10.1111/gcbb.12889>
 42. Shakeel, U., Zeng, Y., Khan, M.R., Song, J., 2026. Valorization of waste lignocellulosic biomass for soil amendment: A critical assessment and strategic framework. *J. Bioresour. Bioprod.* 11, 100230.

<https://doi.org/10.1016/j.jobab.2026.100230>

43. Singh, B., Singh, B. P., and Cowie, A. L. (2010). Characterisation and evaluation of biochars for their application as a soil amendment. *Australian Journal of Soil Research*, 48(7), 516–525.
<https://doi.org/10.1071/SR10058>
44. Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, 22(4), 1315–1324. <https://doi.org/10.1111/gcb.13178>
45. Sohi, S. P., Krull, E., Lopez-Capel, E., and Bol, R. (2010). A review of biochar and its use and function in soil. *Advances in Agronomy*, 105, 47–82. [https://doi.org/10.1016/S0065-2113\(10\)05002-9](https://doi.org/10.1016/S0065-2113(10)05002-9)
46. Spokas, K. A., Cantrell, K. B., Novak, J. M., Archer, D. W., Ippolito, J. A., Collins, H. P., ... Lentz, R. D. (2012). Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *Journal of Environmental Quality*, 41(4), 973–989. <https://doi.org/10.2134/jeq2011.0069>
47. Stavi, I. (2013). Biochar use in forestry and tree-based agro-ecosystems for increasing climate change mitigation and adaptation. *International Journal of Sustainable Development and World Ecology*, 20(2), 166–181. <https://doi.org/10.1080/13504509.2013.776197>
48. Thomas, S. C., & Gale, N. V. (2015). Biochar and forest restoration: A review and meta-analysis of tree growth responses. *New Forests*, 46(5–6), 931–946. <https://doi.org/10.1007/s11056-015-9491-7>
49. Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., ... Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, 327(1–2), 235–246. <https://doi.org/10.1007/s11104-009-0050-x>
50. Verheijen, F. G. A., Jeffery, S., Bastos, A. C., van der Velde, M., and Diafas, I. (2010). Biochar application to soils: A critical scientific review of effects on soil properties, processes and functions (EUR 24099 EN). Office for the Official Publications of the European Communities.
51. Verheijen, F. G., Bastos, A. C., Vasques, A., Mesquita, R., Keizer, J. J., Silva, F. C., ... and Pinto, G. (2022). Biochar increases water use efficiency in eucalypt plants under water and nutrient limitation, with trade-offs under non-limiting conditions. *Journal of Soil Science and Plant Nutrition*, 22(2), 1732–1742. <https://doi.org/10.1007/s42729-022-00767-2>
52. Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., and Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, Article 56.
<https://doi.org/10.1038/ncomms1053>
53. Wrobel-Tobiszewska, A., Boersma, M., Sargison, J., Adams, P., and Jarick, S. (2015). An economic analysis of biochar production using residues from Eucalypt plantations. *Biomass and Bioenergy*, 81, 177–182. <https://doi.org/10.1016/j.biombioe.2015.07.004>
54. Xu, W., Xu, H., Delgado-Baquerizo, M., Gundale, M. J., Zou, X., and Ruan, H. (2023). Global meta-analysis reveals positive effects of biochar on soil microbial diversity. *Geoderma*, 436, 116528. <https://doi.org/10.1016/j.geoderma.2023.116528>
55. Yang, H., Fan, S., Jiang, M., Hu, Y., Chen, X., Chen, C., Liu, W., Zeng, Y., Peng, K., Wang, Y., Wang, G., Wu, Y., 2025. Biochar–organic fertilizer synergy drives microbial-mediated C-sequestration and N-

cycling in mixed forests toward sustainability. J. Environ. Manage. 392, 126892.

<https://doi.org/10.1016/j.jenvman.2025.126892>

56. Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., and Sabir, M. (2016). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using mixed-effects modeling. Field Crops Research, 191, 1–12. <https://doi.org/10.1016/j.fcr.2016.02.012>
57. Zhang, N., Xing, J., Wei, L., Liu, C., Zhao, W., Liu, Z., ... and Zhang, P. (2025). The potential of biochar to mitigate soil acidification: a global meta-analysis. Biochar, 7(1), 49. <https://doi.org/10.1007/s42773-025-00451-5>

Figures



Figure 1

(a) Geographic location of the trial at Vale Domingos, including i) Flat area and ii) Terrace area. (b, c, d) Soil tillage before planting and local soil preparation. (e) The *Eucalyptus globulus* plants before planting. (f, g) Installation stages of the trial.

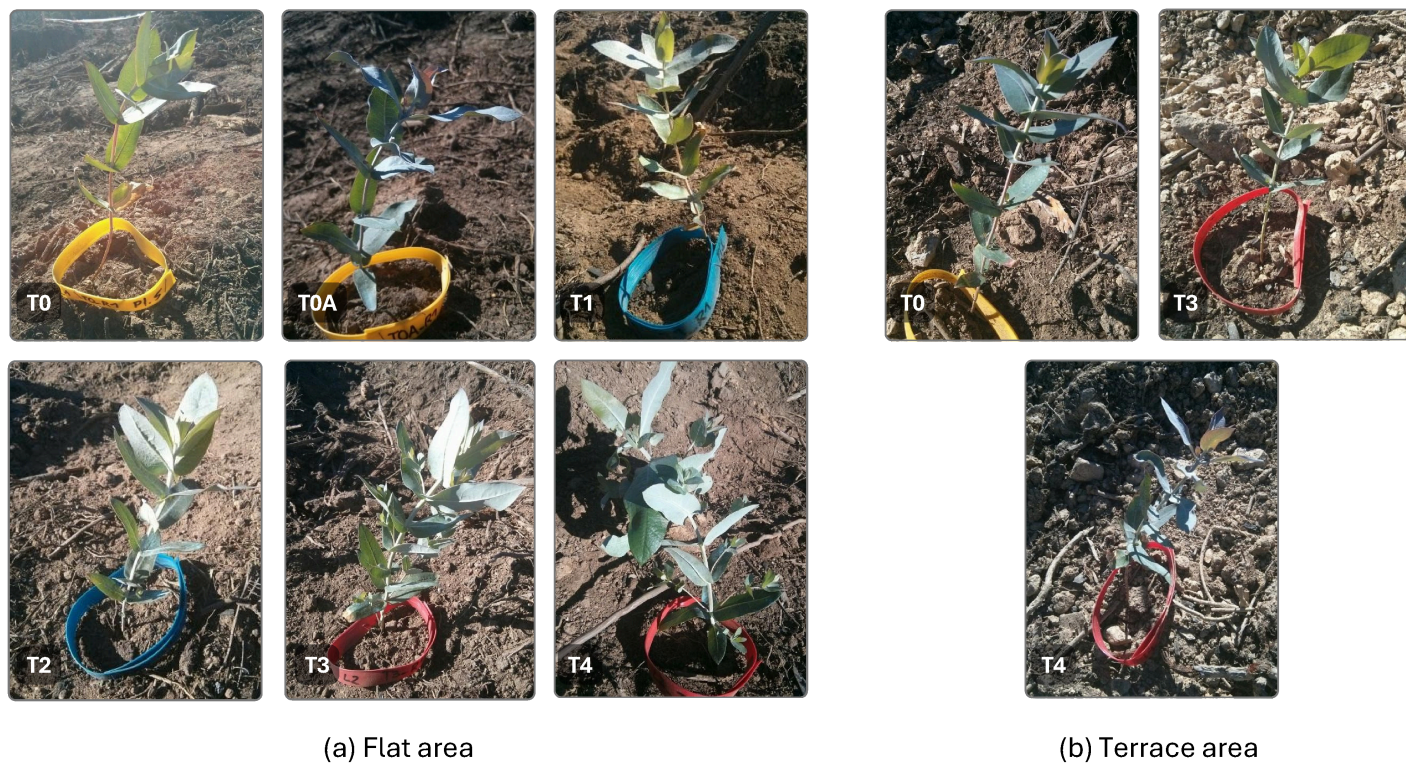


Figure 2

Conditions of the plants in different treatments after installation in (a) Flat area, including T0, T0A, T1, T2, T3, and T4, and (b) Terrace area, including T0A, T3, and T4.

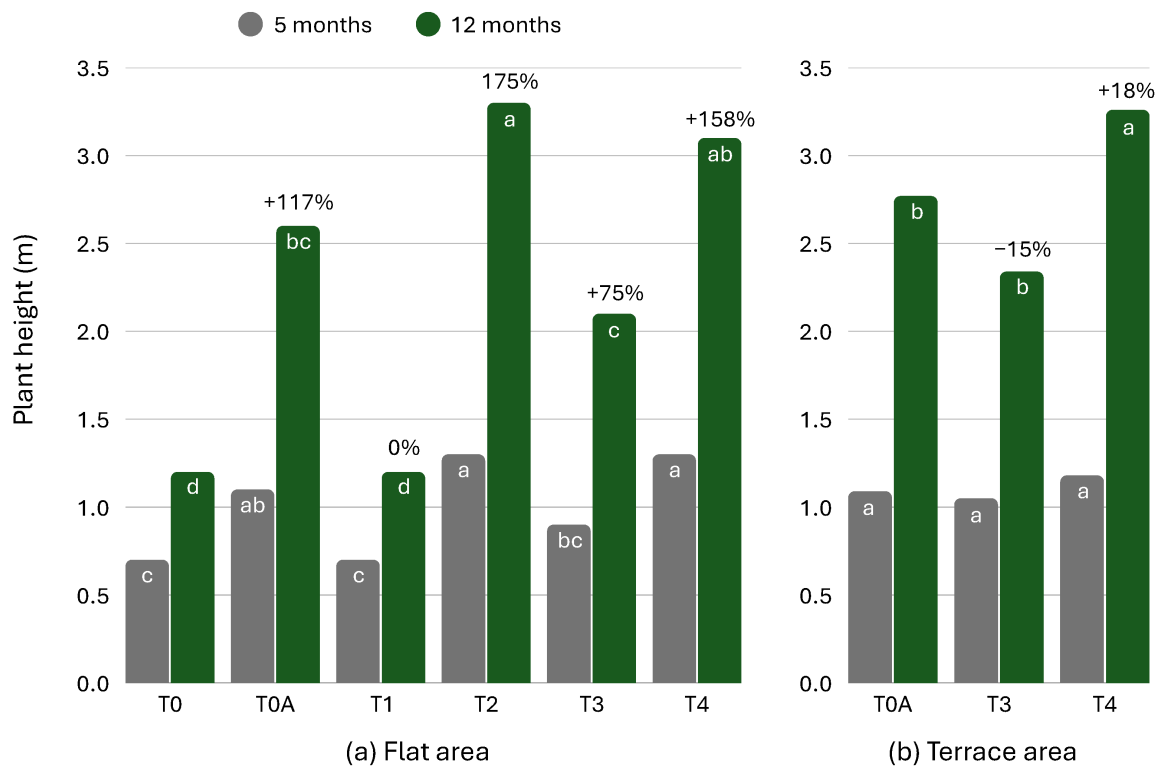


Figure 3

Mean height of *Eucalyptus globulus* at 5 and 12 months after planting under different treatments in the (a) flat area and (b) terraced area. Relative changes (%) are shown for the 12-month measurements only and were calculated with respect to the area-specific control, defined as T0 (control without fertilisation) for the flat area and T0A (control with NPK) for the terraced area. Different lowercase letters indicate statistically significant differences among treatments within each sampling time according to Tukey's HSD test ($p < 0.05$). $n = 3$.

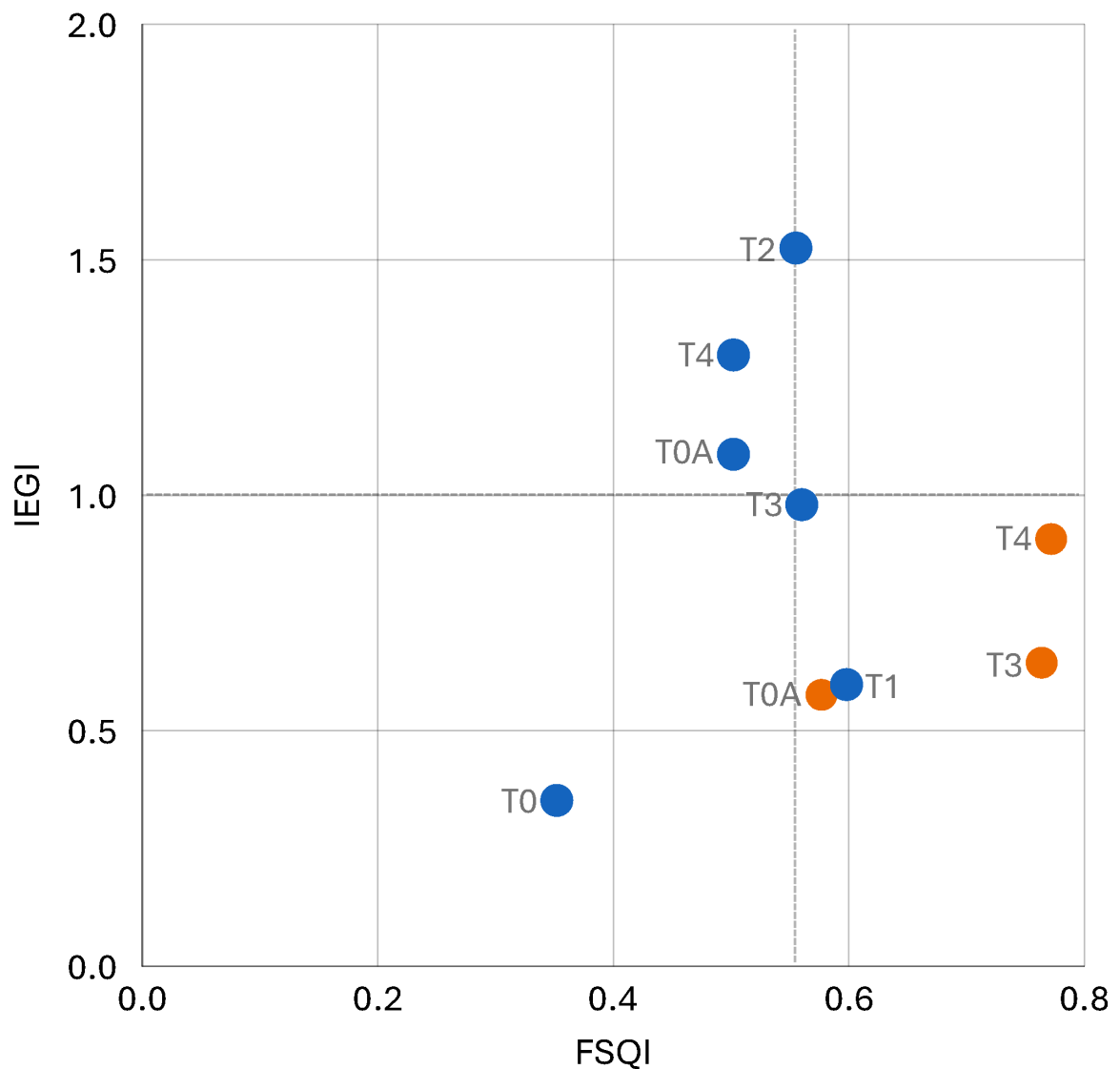


Figure 4

Relationship between Forest Soil Quality Index (FSQI) and Integrated *Eucalypt* Growth Index (IEGI) for all treatments at 12 months after planting. Points represent treatment means in flat (blue) and terraced areas (orange). Dashed lines indicate reference thresholds (FSQI = 0.55; IEGI = 1.0) used to visualise differences in soil–plant coupling. Combined biochar–fertiliser treatments showed the highest IEGI values within each area, although their positions relative to the exploratory FSQI and IEGI thresholds differed between the flat and terraced areas.

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