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Ameliorating Sandy Loam Soils: Assessing Soil Nutrient Dynamics and Crop Performance under Variable Rates of Hydrogel, Humic acid and Biochar

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Authors' contributions

This work was carried out in collaboration among all authors. Author MR designed and conducted the study, performed the statistical analysis, managed the literature searches, wrote the protocol, and wrote the first draft of the manuscript. Authors PN and NKB managed the analyses of the study and edited the manuscript. All authors read and approved the final manuscript.

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Abstract

Background: Sandy loam soils are generally low in organic matter and have poor water and nutrient retention, which limits crop productivity. Soil amendments such as hydrogel, humic acid, and biochar are increasingly used to improve soil quality and enhance plant growth. However, their comparative effectiveness under sandy loam conditions is not well understood, making this study relevant for sustainable soil management.

Aims: To evaluate the individual potential of variable rates of specific soil amendments -hydrogel, humic acid, and biochar, to improve the productivity and overall health of sandy loam soils, which are typically hindered by low organic matter and poor water retention.

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Study Design: Three set of pot culture experiments were carried out using hydrogel, humic acid and biochar. The design used was completely randomized design (CRD).
Place and Duration of Study: Pot culture experiments were conducted at College of Agriculture, Padannakkad, Kasaragod, Kerala, India, from December 2024 to May 2025.
Methodology: Three independent pot experiments were conducted with 5 replications and 4 treatments of hydrogel,8 treatments of humic acid (comprising variable rates of plant derived and synthetic humic acid) and 8 treatments of biochar (comprising variable rates of hardwood and rice husk biochar). Total number of pots used were 100. The test crop was chilli (*var* Anugraha).
Results: The three amendments optimized soil health and crop growth in different way. Hydrogel application at 3 kg ha^{-1} optimized soil aggregate stability, reduced bulk density, and also facilitated the reproductive growth, resulting in maximum dry matter production (35.3 g). Synthetic humic acid at 15 kg ha^{-1} structurally stabilized the soil while significantly enhancing soil organic carbon (SOC), available nitrogen and available potassium. Among the biochar treatments, hardwood biochar consistently outperformed rice husk biochar, yielding significantly higher SOC, nitrogen availability, dry matter accumulation and final fruit yield.
Conclusion: Optimal rate of application of these amendments significantly improved the physico-chemical properties of sandy loam soils, demonstrating that while biochar is most effective for crop yield, hydrogel and humic acid were superior for structural stability and moisture retention, offering a sustainable pathway for managing coarse-textured agricultural soils.

Keywords: Sustainable agriculture; moisture retention; natural chelator; carbon sequestration; aggregate stability; productivity enhancement; coarse textured soil.

1. Introduction

The worldwide soil resources are under intense pressure as an estimated 33 percent of global land is being degraded due to erosion, salinization, compaction, acidification, and chemical pollution. Every year, 25-40 billion tons of fertile topsoil are lost, substantially reducing the capacity of soil to recycle nutrients, store water and sequester carbon (Food and Agriculture Organization of the United Nations, 2015). If unabated, these trends threaten food security, raise the cost of agricultural production and impair ecosystem resilience. Recent studies have highlighted the potential of soil amendments such as hydrogel, humic acid, and biochar to enhance soil functionality, particularly in coarse-textured soils like sandy loams. Hydrogels are superabsorbent polymers with high water-holding capacity and have been shown to reduce irrigation needs, improve moisture availability during dry spells and support better root development in crops. Humic acid, a key component of soil organic matter, enhances cation-exchange capacity, stimulates microbial activity and improves nutrient uptake by forming stable organo-mineral complexes. Biochar, a carbon-rich product of biomass pyrolysis is widely recognized for its ability to improve soil structure, increase porosity, enhance nutrient retention and contribute to long-term carbon sequestration. Although each amendment has been widely studied in various agroecosystems, there remains limited understanding of how these amendments perform individually and comparatively in sandy loam soils. The sandy loam soils in Kerala, a southern state of India, is generally less productive due to low organic matter, poor water holding capacity and low nutrient retention. Hence, this study was conducted to assess the impact of specific amendments (hydrogel, humic acid and biochar) on improving soil quality (physical and chemical health) and crop yield in the sandy loam soils and to identify viable strategies for promoting resilient agricultural systems in the region.

2. Material and Methods

2.1 Description of the Study Area

Pot culture experiments were conducted at College of Agriculture, Padannakkad, Kasaragod, Kerala, India (12°15’30” N latitude and 75° 7’ 2” E longitude) to evaluate the effect of specific soil amendments (hydrogel, humic acid and biochar) on various soil properties and crop yield with chilli (variety *Anugraha*) as the test crop (Fig. 1). Soil samples required for the conduct of the study were collected from Instructional farm 2 of College of Agriculture, Padannakkad, Kasaragod, Kerala, India situated in Agro-Ecological Unit 2 (AEU 2) *i.e.* Northern Coastal Sandy Soils (12° 14’ 55’’ N latitude and 75° 8’ 7’’ E longitude (Fig. 2).

Fig. 1. Layout of the pot culture experiments

Fig. 2. Study area at Instructional farm 2

2.2 Experimental Design and Treatments

Three pot culture experiments were conducted in CRD (Completely Randomised Design) design with five replications. Treatments of the experiments are as per the following details;

Experiment no.1:

T_1- Recommended dose of fertilizers (RDF)*, lime and FYM (farm yard manure) as per the KAU POP (Kerala Agricultural University Package of Practices)
T_2 -T_1+Hydrogel@ 2 kg ha^{-1}**
T_3 -T_1+Hydrogel@ 3 kg ha^{-1}
T_4-T_1+ Hydrogel@ 5 kg ha^{-1}

*Recommended dose of fertilizers in T_1- Lime @ 250 kg ha^{-1}, FYM @ 20 t ha^{-1}, NPK (Urea, Raj Phos and Potash) @ 75:40:25 kg ha^{-1}

**1:10 hydrogel–soil mixture was prepared and placed in the root zone of the plants in respective pots.

Experiment no.2:

T_1- RDF, lime and FYM as per KAU POP
T_2 - RDF, lime and 50 % FYM as per KAU POP
T_3 - T_2 + synthetic HA (humic acid) @10kg ha^{-1}***
T_4 - T_2 + synthetic HA @15kg ha^{-1}
T_5 - T_2+ Plant derived humic acid (PDHA)@ dosage that gives equivalent carbon of HA from T_3****
T_6 - T_2+ PDHA@ dosage that gives equivalent carbon of HA from T_4
T_7 - T_5 + synthetic HA @ 10kg ha^{-1}
T_8 - T_6 + synthetic HA @ 15kg ha^{-1}

*** Synthetic and plant-derived humic acid were applied as soil drenching at one week after transplantation.

****Plant derived humic acid (PDHA) was prepared according to the method described by Khan et al., (2013). One part of fresh green leaves of *Chromolaena odorata* was soaked overnight in twenty parts of 0.1N potassium hydroxide. Contents were then sieved with mesh no 115, followed by centrifugation of the extract at 5000 rpm for 30 minutes. The supernatant obtained was neutralized with dilute hydrochloric acid (0.01N) and stored.

Experiment no.3:

T_1 - RDF, lime and FYM as per KAU POP
T_2 - RDF, lime and 50 % FYM as per KAU POP
T_3 – T_2+ Rice husk biochar @ 5 t ha^{-1}*****
T_4 – T_2+ Rice husk biochar@ 10 t ha^{-1}
T_5 – T_2+ Rice husk biochar@ 15 t ha^{-1}
T_6 – T_2+ Hardwood biochar@ 5 t ha^{-1}
T_7 – T_2+ Hardwood biochar @ 10 t ha^{-1}
T_8 – T_2+ Hardwood biochar @ 15 t ha^{-1}
*****Biochar was applied as basal application along with FYM.

2.3 Analysis of Soil Samples

Soil samples were analysed for physical and chemical properties as detailed below in Table 1.

2.4 Analysis of Plant and Fruit Samples

After harvest, the plants were uprooted and both plant material and fruits were analysed for nutrient content as shown in Table 2.

Table 1. Different analytical methods followed for plant and fruit nutrient analysis

Sl. No.	Parameter	Method	Reference
1	Total Nitrogen	Modified Kjeldhal digestion method	Jackson (1958)
2	Total Phosphorus	Vanadomolybdate yellow colour method	Piper (1966)
3	Total Potassium	Flame photometry	Jackson (1973)
4	Tota Calcium	Atomic absorption spectrophotometry	Jackson (1973)
5	Total Magnesium	Atomic absorption spectrophotometry	Jackson (1973)
6	Total Sulphur	Turbidimetric method followed by spectrophotometric estimation	Bhargava & Raghupathi (1993)

2.5 Biometric Observations of Plant and Fruit

Plant height, total plant biomass, number of fruits per plant, fruit length, fruit weight, dry matter accumulation and fruit yield were measured manually.

2.6 Statistical Analysis of the Data

The results of the experiment were analysed by one-way analysis of variance (ANOVA) and the treatment means were compared with Duncan Multiple Range Test (DMRT) using GRAPES software (General R-shiny-based Analysis Platform Empowered by Statistics) https://www.kaugrapes.com/home).

Table 2. Standard procedures for soil analysis

Sl.No.	Parameter	Method	Reference
1.	Bulk density	Core method	Gupta & Dakshinamoorthi (1980)
2.	Particle density	Pycnometer method	Blake & Hartge (1986)
3.	Water holding capacity	Core method	Gupta & Dakshinamoorthi (1980)
4.	pH (1:2.5 ratio)	Potentiometry	Jackson (1958)
5.	EC (1:2.5 ratio)	Conductimetry	Jackson (1958)
6.	Organic carbon	Wet oxidation method	Walkley & Black (1934)
7.	Available N	Alkaline permanganate method	Subbiah & Asija (1956)

Sl.No.	Parameter	Method	Reference
8.	Available P	Bray extraction and spectrophotometric estimation	Bray & Kurtz (1945)
9.	Available K	Flame photometry	Jackson (1973)
10.	Available Ca & Mg	Titration with EDTA	Hesse (1971)
11.	Available S	Calcium chloride extraction and spectrophotometric estimation	Massoumi & Cornfield (1963)

3. Results and Discussion

3.1 Initial Soil Properties

The initial properties of soil at the experimental site are given in Table 3. Bulk density and particle density of soil were 1.3 Mg m^{-3} and 2.2 Mg m^{-3} respectively. Soil was moderately acidic in reaction with a pH of 5.4 and electrical conductivity (EC) was 0.19 dS/m, indicating low soluble salt content in soil. The soil organic carbon (0.66%), available nitrogen (301.056 kg/ha) and potassium (212.46 kg/ha) content in the soil was in medium range while available phosphorus (164.69 kg/ha) and sulphur (177.8 ppm) contents were high.

Table 3. Initial soil properties

Sl. No.	Parameter	Value	Rating
1	pH	5.4	Moderately acidic
2	Electrical conductivity (dS/m)	0.19	Non-saline
3	Soil organic carbon (%)	0.66	Medium
4	Soil available nitrogen(kg/ha)	301.056	Medium
5	Soil available phosphorus(kg/ha)	164.69	High
6	Soil available potassium(kg/ha)	212.46	Medium
7	Soil available sulphur (ppm)	177.8	Sufficient

3.2 Physico-chemical Response of Soil to Amendments

3.2.1 Response to Hydrogel

The application of hydrogel did not exhibit significant influence on soil pH and electrical conductivity (Table 4), which suggests that the hydrogel used is chemically inert and does not alter the basic chemical equilibrium in soil solution. Similar findings were observed by Ali et al., (2024), who reported that polyacrylate-based super absorbent polymers maintain reaction equilibrium at rhizosphere, making them compatible for acidic soil conditions.

The bulk density of soil significantly varied with hydrogel application. Lowest value (1.168 Mg/m3) was recorded in treatment T3. As the hydrogel swell, it displaces the soil particles and eventually increase the soil pore space, thereby lowering the bulk density. A study by Womack et al., (2022) suggested that hydrogel increases soil porosity and lowers mechanical resistance for chilli root penetration. Particle density of soil did not vary significantly among the treatments (Table 4).

Table 4. pH, electrical conductivity, bulk density and particle density of soil treated with hydrogel

Treatment	Soil pH	Electrical conductivity(dS/m)	Bulk density (Mg/m3)	Particle density (Mg/m3)
T1	5.232	0.120	1.380^{a}	2.530
T2	5.304	0.108	1.356^{a}	2.520
T3	5.310	0.106	1.168^{b}	2.556
T4	5.204	0.122	1.366^{a}	2.548
SE(m)	0.115	0.008	0.021	0.028
CD	NS	NS	0.19	NS

The stability of soil aggregates significantly varied among all the treatments (Fig 3). Maximum percentage of water stable aggregates was observed in soil treated with 3kg of hydrogel per hectare. Mean weight diameter of the aggregates was also higher in the same treatment, indicating that the molecules of hydrogel act as cross-linking agents that bind soil particles together and improves soil aeration and aggregation (Maksimova et al., 2023). A decline in water-stable aggregates and mean weight diameter was observed at the maximum hydrogel application rate. This is due to the excessive swelling pressure exerted by the surplus polymer which causes dispersion of soil particles rather than aggregation (Nadler et al., 1996).

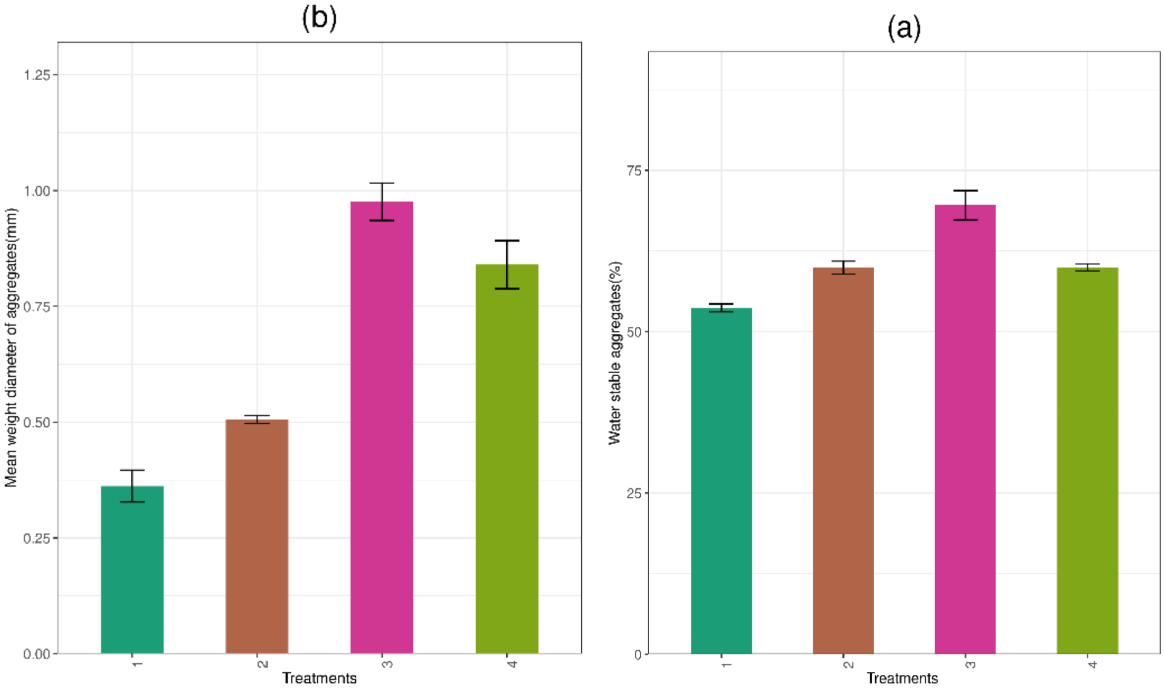


Fig. 3. (a)Water stable soil aggregates and (b)Mean weight diameter of aggregates under various rates of hydrogel

Increasing dosage of hydrogel had significantly affected the water holding capacity (WHC) of soil (Fig 4). Maximum WHC (24%) was recorded in treatment T4, followed by T3 (22%). According to Agbna and Zaidi (2025), swollen hydrogel particles are minute water reservoirs that function as buffer for plants during irrigation interval and extend the permanent wilting point of soil.

A significantly higher soil organic carbon was noted in treatment t3 when compared with other treatments (fig 4). Yang et al., (2022) suggested that the organic carbon in the soil get protected from oxidation by means of enhanced root exudation, presence of microbial metabolites facilitated by constant moisture availability and improved soil aggregate stability by hydrogel action. In another study by saha et al., (2020), it was observed that hydrogel promoted root proliferation, contributing directly to better soil carbon inputs.

Available nitrogen in soil was highest in soil treated with hydrogel @ 2kg ha^{-1}. This significant increase in nitrogen may be due to the hydrophilic nature of the hydrogel, which reduces leaching losses of nitrates by maintaining optimum moisture in the root zone. A decline in nutrient content was observed at higher doses, likely due to "dilution effect" causing temporary immobilization of nutrients within the swollen polymer. Similar result was reported by Mikhailidi et al., (2024), who observed that optimum rate of hydrogel application improves nutrient retention, whereas overdosage might hinder nutrient mobility.

The highest value of available phosphorus (211.4$kgha^{-1}$) was obtained from treatment T3 (Table 5). The synergistic effect of farm yard manure and hydrogel in the treatment might have facilitated the release of organic acids, that helped in solubilizing inorganic phosphates. Purkaystha et al., (2025) observed that hydrogel-treated soils maintain a higher level of phosphorus due to the hydration of the soil-root interface. Available potassium content in soil varied non-significantly among the treatments. The reason for this was explained by Oliveira et al., (2026) that potassium dynamics in sandy loam soils are more influenced by cation exchange capacity and mineral composition of soil rather than by moisture-retaining polymers alone.

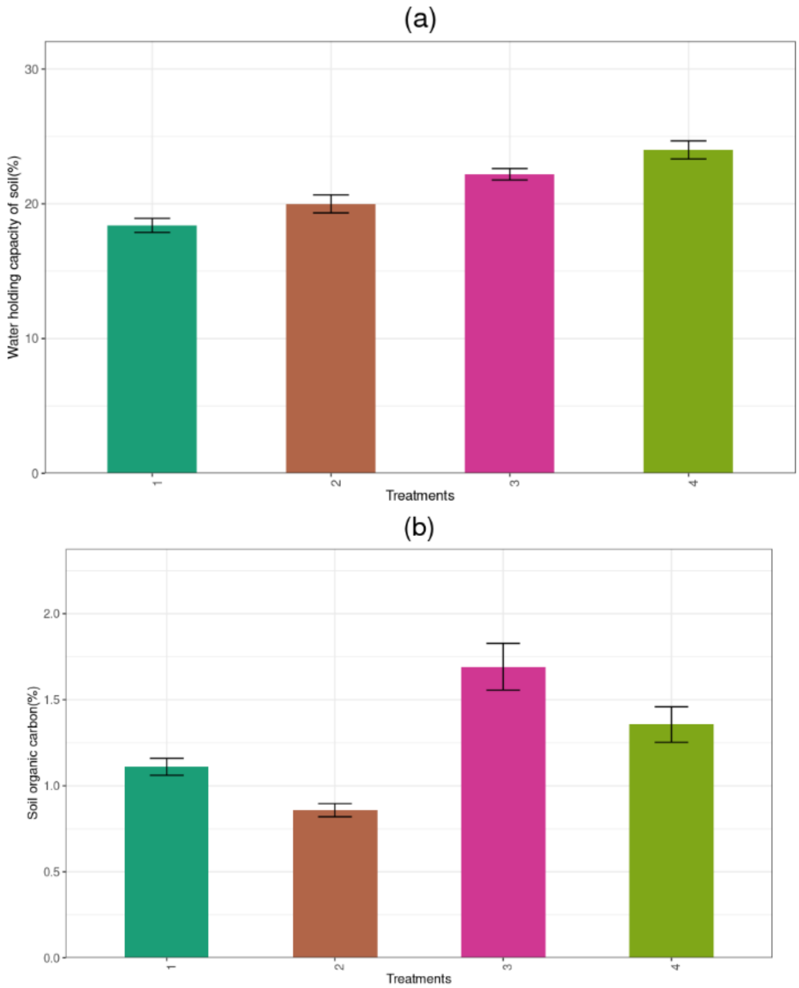


Fig. 4. Effect of hydrogel on (a) water holding capacity of soil and (b) soil organic carbon content of soil.

Table 5. Available primary nutrient content in soil treated with hydrogel

Treatments	Available N (kg/Ha)	Available P (kg/Ha)	Available K (kg/Ha)
T1	57.379^{b}	173.802^{b}	212.173
T2	157.26^{a}	141.075^{c}	188.518
T3	71.051^{b}	211.411^{a}	243.734
T4	42.504^{c}	131.645^{d}	213.853
SE(m)	4.901	2.886	19.973
CD	2.96	2.27	NS

The available calcium content in the soil varied significantly among treatments and the highest value (596 mg/kg) was recorded in T2 (Fig. 5). Many studies reported that moderate dose of hydrogel favors the retention of calcium ions within the soil by reducing vertical leaching. At higher doses, carboxylic groups of polymers tightly sequester divalent cations, making them less available in the soil solution (Maksimova et al., 2023). Lowest value of available magnesium was observed in the treatment that reported highest available calcium content (T2). This is because, the balance between calcium and magnesium in the soil solution is sensitive to moisture retaining polymers, capable of retaining one cation over the other depending upon the density of cross-linking in the polymer (Ben-Hur, 2006). The recovery of higher magnesium level at higher dose of hydrogel might be due to change in the polymer's expanded volume that allows magnesium accumulation. A comparatively higher value of available sulphur (22.542 mg/kg) was recorded in T3 (22.542 mg/kg), which indicates that balance of moisture retention in hydrogel-treated soils reduces the percolation losses of the highly mobile sulphate ions in soils.

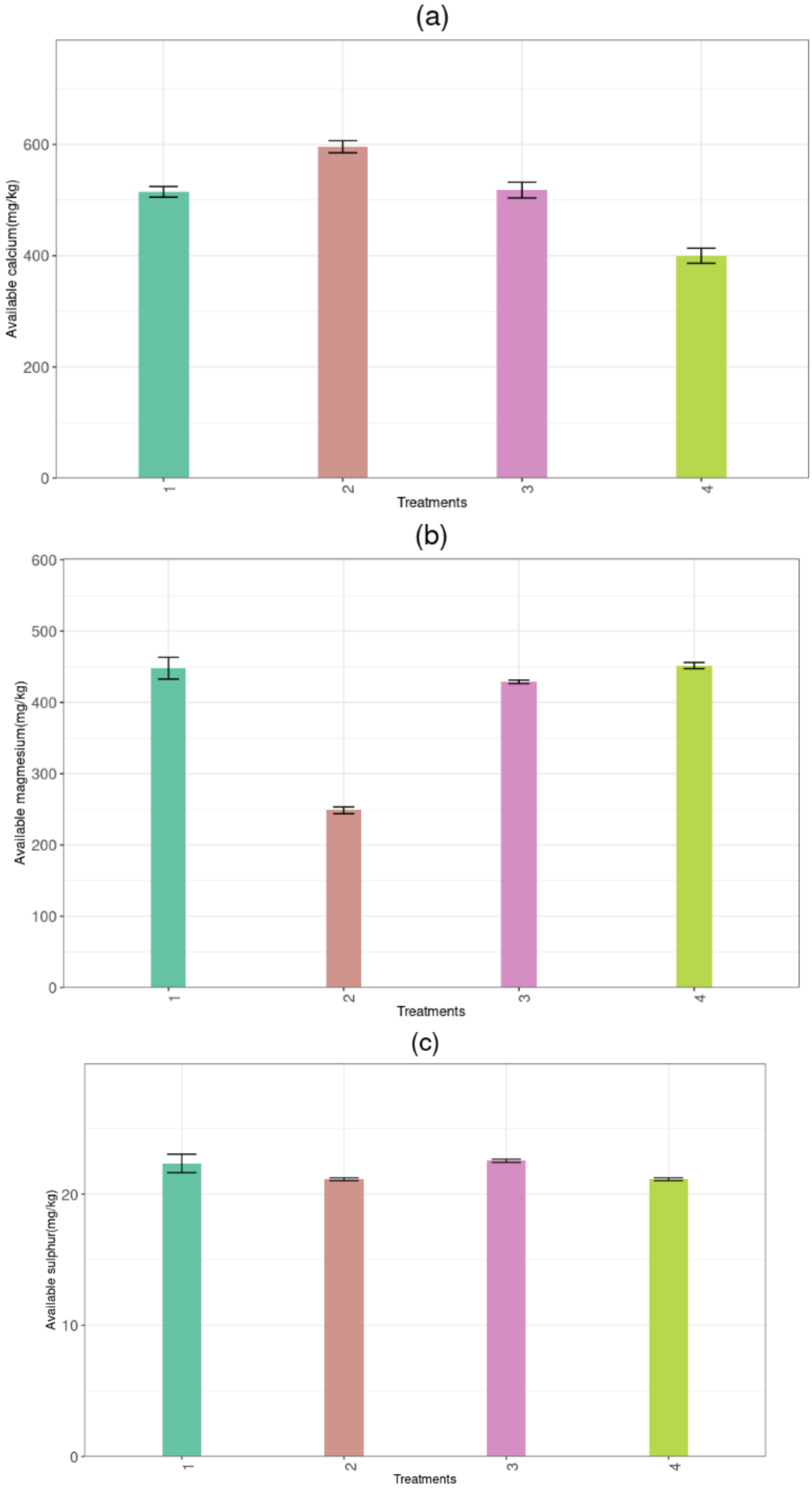


Fig. 5. Available secondary nutrients in soil treated with hydrogel

3.2.2 Response to Humic Acid

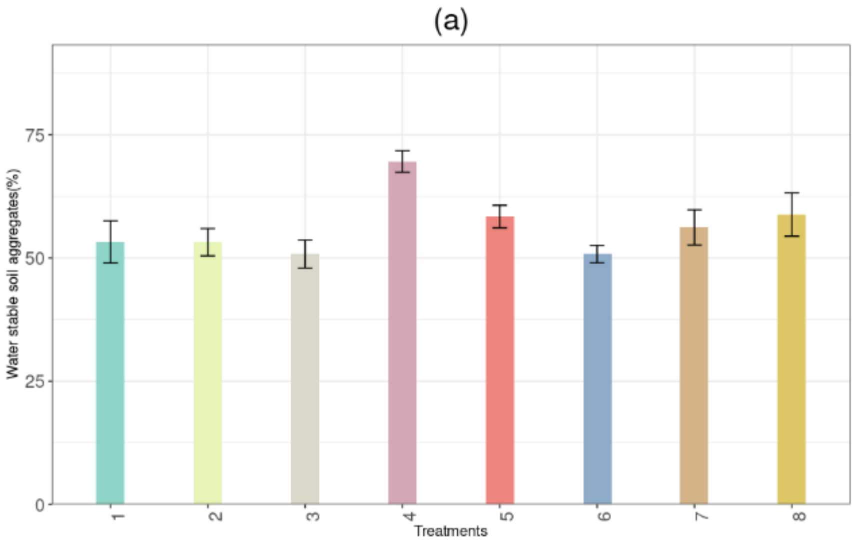
Soil pH was not significantly influenced by humic acid treatments (Table 6). This indicates that despite the alkaline nature of humic acid, the buffering capacity of the soil was sufficient to resist the change in acidic reaction of soil. Treatment T8 exhibited the lowest value (0.09 dS/m) of soil electrical conductivity, which is attributed to the improved soil structure and ion exchange capacity by humic acid, which in turn facilitates the regulated release of nutrients (Bera et al., 2024). The colloidal interaction of soil and humic acid helps to bind the mineral grains and increases pore space. The bulk density of soil was lowest (1.092 Mg m^{-3}) in T4. Similar findings were reported by Yang et al., (2021). Particle density remained non-significant as it is a function of mineralogical composition of soil.

Table 6. Soil pH, EC, bulk density and particle density as influenced by humic acid treatments

Treatments	pH	EC (dS/m)	Bulk density (Mg m^{-3})	Particle density (Mg m^{-3})
T1	5.238	0.470^{a}	1.416^{a}	2.550
T2	5.224	0.102^{b}	1.338^{ab}	2.486
T3	5.244	0.108^{b}	1.344^{ab}	2.464
T4	5.302	0.112^{b}	1.092^{d}	2.504
T5	5.364	0.100^{b}	1.332^{b}	2.526
T6	5.282	0.114^{b}	1.284^{b}	2.568
T7	5.312	0.108^{b}	1.352^{ab}	2.514
T8	5.396	0.090^{b}	1.192^{c}	2.526
SE(m)	0.041	0.008	0.028	0.041
CD	NS	0.12	0.21	NS

The water stable soil aggregates and mean weight diameter of the aggregates were higher in treatment T4 (Fig 6), suggesting that synthetic humic acid provides more binding effect on soil particles than the plant derived humic acid. A study by Murphy (2015) revealed that humic acids facilitate the macro-aggregation process and improve the soil aggregate stability.

A significant variation in water holding capacity of soil was observed among the treatments and the highest value (25%) was recorded in treatment T5 (Fig 7) which is a direct consequence of the hydrophilic nature of humic substances. According to Nabi et al., (2025), integrated nutrient management practices involving humic acid significantly improves the volumetric water content of the rhizosphere. Application of synthetic humic acid @15kg/ha showed the highest soil organic carbon (1.8%) which was significantly superior over rest of the treatments (Fig 7). Many studies revealed that humic acid directly contributed to the soil carbon pool. Das (2023) observed that humic acid promoted carbon sequestration in Indian Inceptisols by storing carbon within stable micro-aggregates.



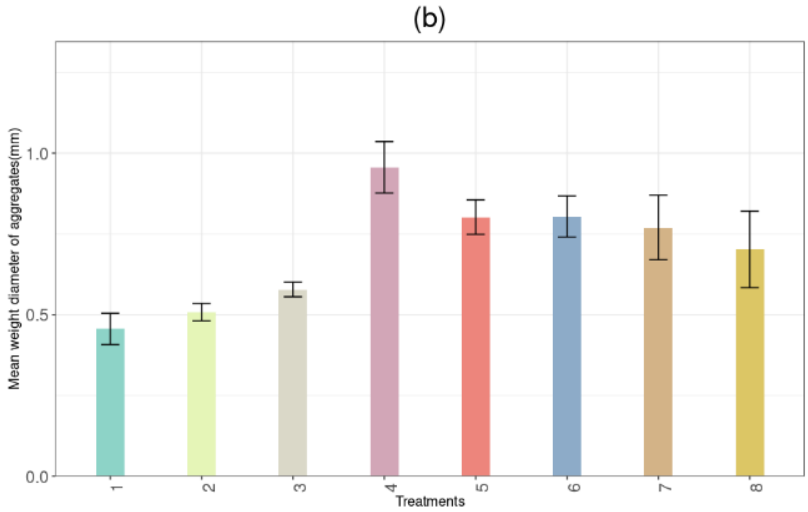


Fig. 6. (a)Water stable soil aggregates and (b) mean weight diameter of aggregates of soil treated with various dose of humic acid

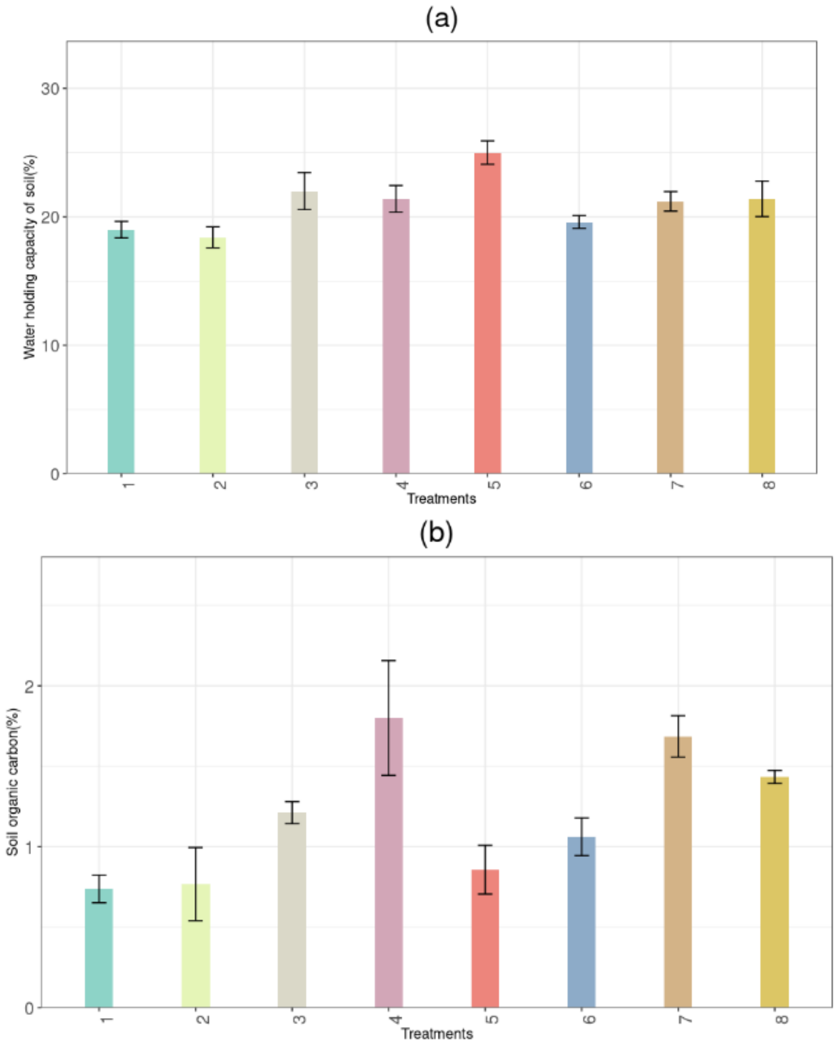


Fig. 7. Effect of various dose of humic acid on (a) Soil water holding capacity and (b) Soil organic carbon content

Available nitrogen was maximum (174.4kg/ha) in T4 which was on par with T3 (Table 7). Similar result was obtained by Kong et al., (2022) who reported that humic acid treated urea reduced nitrogen losses by 25.51% compared to untreated urea. Available phosphorus was highest (155.30 kg/ha) in treatment T7. Humic acid acts as a ligand by occupying the adsorption sites of iron and aluminium oxides, that would otherwise bind phosphorus (Larsen et al., 1959). Soil potassium availability was significantly higher (225 kg/ha) in treatment T4 and T7, which might be attributed to the high cation exchange capacity of humic substances. Zhu et al., (2022) suggested that lignite derived potassium humates enhance the retention of K^+ ions in the rhizosphere and prevent its leaching into deeper soil layers. Humic acid acts as a natural chelator, which was reflected in significantly higher value of available calcium (690 mg/kg) and magnesium (321.8 mg/kg) in treatments T8 and T6 treatments respectively. The synergistic effect of synthetic as well as plant derived fraction of humic acid ensured that these divalent cations remain bioavailable. Similar findings were reported by Alvarez et al. (2004). Available sulphur was significantly higher (23.42 mg/kg) in T4. Humic acid is a good source of carbon for sulphur-oxidizing bacteria, that converts organic sulphur into plant-available forms (Malik et al., 2021).

Table 7. Available primary and secondary nutrient content in soil treated with humic acid

Treatments	Available N(kg/Ha)	Available P(kg/Ha)	Available K(kg/Ha)	Available Ca(mg/kg)	Available Mg(mg/kg)	Available S(mg/kg)
T1	115.448^{b}	124.112^{bc}	153.619^{d}	418^{e}	225.2^{e}	22.727^{ab}
T2	63.944^{c}	138.250^{ab}	187.376^{c}	598^{b}	207.4^{f}	19.637^{c}
T3	170.101^{a}	115.448^{cd}	77.482^{e}	400^{ef}	238.6^{d}	22.365^{b}
T4	174.446^{a}	106.371^{cd}	225.389^{a}	600^{b}	228.4^{e}	23.418^{a}
T5	154.829^{ab}	103.162^{d}	185.069^{c}	540^{c}	260.6^{c}	10.040^{f}
T6	139.488^{ab}	106.016^{cd}	205.005^{b}	452^{d}	321.8^{a}	22.952^{ab}
T7	123.667^{b}	155.295^{a}	225.456^{a}	398^{f}	239.6^{d}	13.293^{e}
T8	151.466^{ab}	149.165^{a}	203.526^{b}	690^{a}	306.0^{b}	15.252^{d}
SE(m)	15.13	6.68	1.178	6.285	3.305	0.295
CD	5.01	3.32	1.39	3.2	2.34	0.69

3.2.3 Response to Biochar

Soil reaction (pH) was not significantly influenced by the treatments (Table 8). According to Khan et al., (2026), the impact of biochar on soil pH is dependent on the initial pH and duration of the cropping cycle of feedstock used for biochar production. Treatment involving hardwood biochar showed lowest value for soil electrical conductivity (0.084 dS/m). This is likely due to higher surface area of hardwood biochar, which adsorb excess soluble salts from soil (Chrysargyris et al., 2024). Bulk density of soil was lowest (1.168 Mg/m^3) in soil treated with rice husk biochar @ 5 t ha^{-1}. This indicates that rice husk biochar with a lower density and high internal porosity physically displaces denser soil particles. A similar reduction (below 1.1 g/cm^3) in bulk density of soil treated with 10% of rice husk biochar was reported by Zahro et al., (2024).

Table 8. pH, EC, Bulk density and Particle density of soil under biochar treatments

Treatments	Soil pH	EC (dS/m)	Bulk density (Mg/m3)	Particle density (Mg/m3)
T1	5.286	0.110^{a}	1.190^{c}	2.410
T2	5.184	0.122^{a}	1.340^{ab}	2.538
T3	5.232	0.114^{a}	1.168^{c}	2.498
T4	5.156	0.116^{a}	1.366^{a}	2.556
T5	5.134	0.120^{a}	1.254^{bc}	2.496
T6	5.192	0.084^{b}	1.340^{ab}	2.540
T7	5.198	0.118^{a}	1.372^{a}	2.556
T8	5.186	0.112^{a}	1.240^{bc}	2.488
SE(m)	0.044	0.008	0.039	0.042
CD	NS	0.16	0.25	NS

Hardwood biochar was found better than rice husk biochar in increasing percent water stable aggregates and mean weight diameter of aggregates (Fig 8), with highest values of 70.44% and 0.780 mm respectively in treatment T7. This might be attributed to high content of lignin and stronger functional groups in the hardwood biochar which act as bridge between soil and organic matter, thereby increasing structural stability of soil (Mitchell et al., 2016).

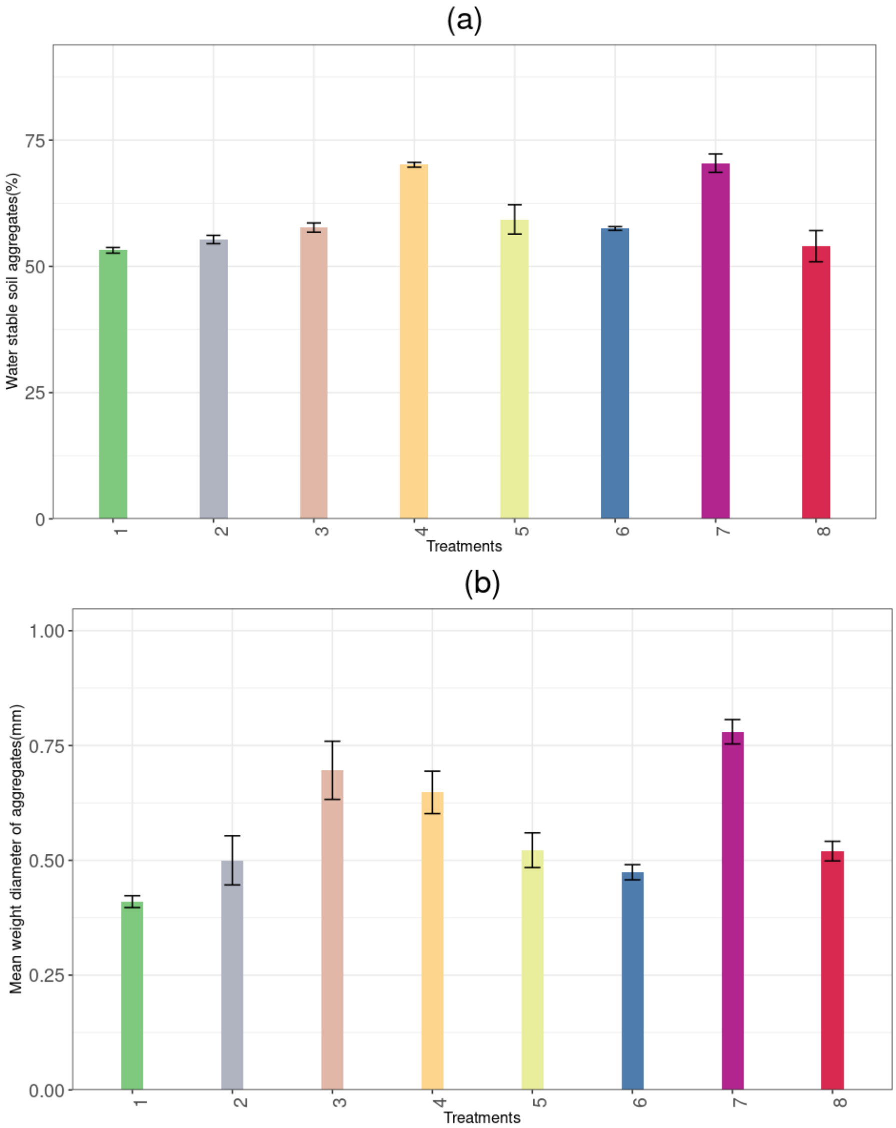


Fig. 8. Effect of biochar on (a)water stable aggregates and (b) mean weight diameter of aggregates

The water holding capacity of soil was significantly increased with biochar application (Fig 9) having maximum value (24.6%) in T7, followed by T6 (24 %). Previous study by Xu et al., (2024**)** reported similar finding that the porous structure of biochar increased storage pores for plant-available water. Soil organic carbon content was highest (1.218%) in treatment T6. As per the findings of Petersen et al., (2023), the stable carbon rich aromatic structure of hardwood biochar resists microbial degradation and helps in long-term carbon sequestration.

Among the treatments, T6 recorded highest available nitrogen content (249.098 kg ha) (Table 9) which may be due to the ability of biochar to adsorb ammonium ions (NH_4^+) and reduce leaching losses (Sun et al., 2019). Application of hardwood biochar @10t/ha resulted in maximum available phosphorus content (146.317 kg/ha). The carboxyl and hydroxyl groups on the surfaces of biochar effectively compete with phosphate ions for exchange sites, leading to reduced phosphorus fixation (Luo et al., 2023). There was no significant difference among the treatments for soil available potassium. Xiu et al., (2026) reported that biochar acts as a potassium scheduling centre, converting the potassium in fertilizer into non-exchangeable fraction to prevent leaching and temporarily lowers the available potassium content.

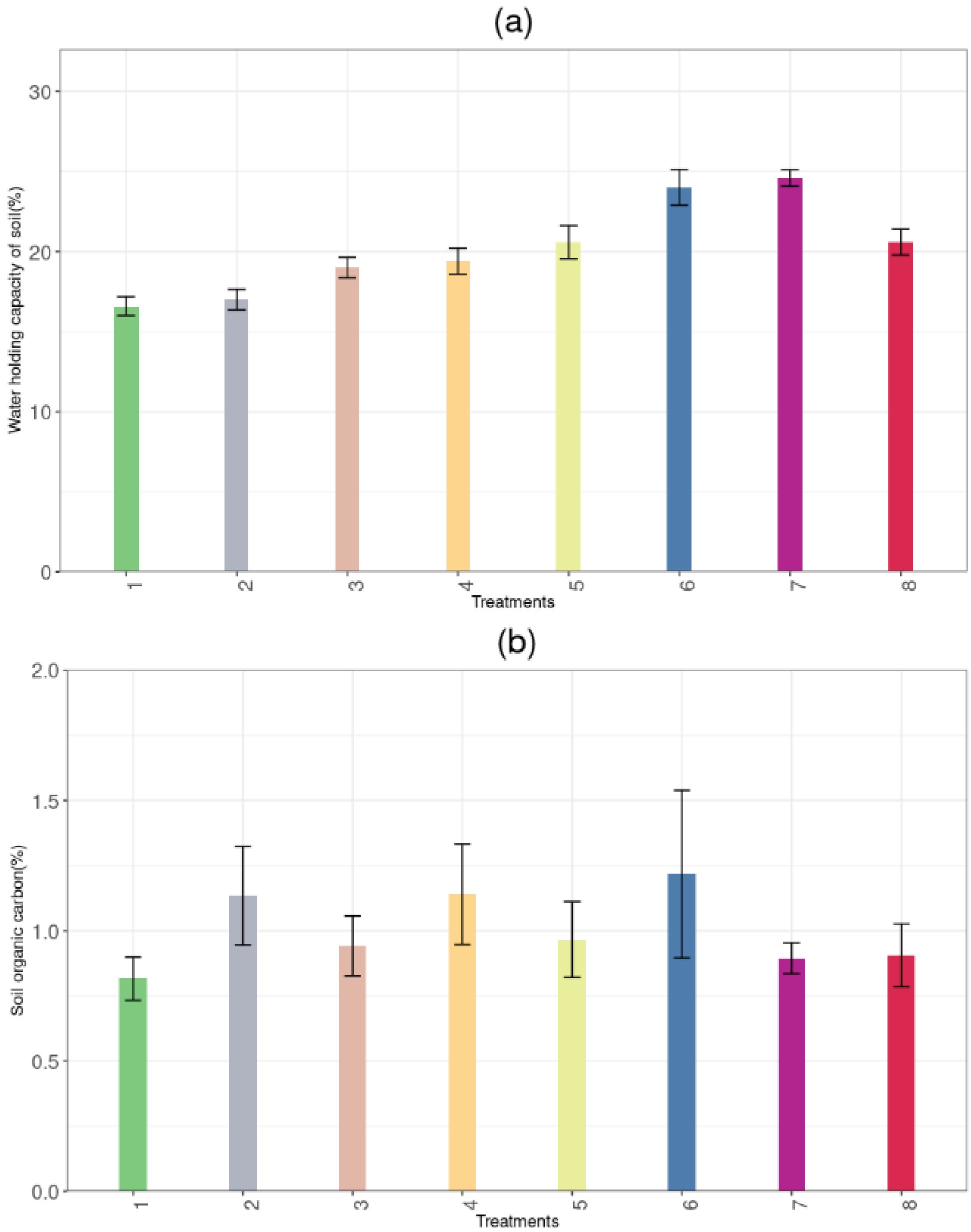


Fig. 9. Influence of biochar on (a) water holding capacity of soil and (b) soil organic carbon

Available calcium content (876 mg kg^{-1}) was highest in treatment T5. This may be due to direct nutrient addition from the ash fraction of biochar and the enhancement of soil cation exchange capacity. This is in conformity with the findings of Xiu et al., (2026) who reported that biochar holds the divalent cations on its oxygen-containing functional groups to prevent leaching losses. Higher content (604.8mg/kg) of available magnesium in T8 is attributed by high cation exchange capacity of hardwood biochar. This is further supported by the findings of Yang et al., (2022) who revealed that biochar promotes the soil microbial activity and activates the stable magnesium pools in soil. There was maximum build up in available sulphur (22.78mg kg^{-1}) in treatment involving hardwood biochar that created an ideal rhizospheric environment for sulphur-mineralizing bacteria (DeLuca et al., 2009). However, a tremendous reduction in sulphur content in treatment T8 suggested that at very high rate of biochar application, sulphur gets immobilized.

Table 9. Available primary and secondary nutrients in soil treated with biochar

Treatments	Available N(kg/Ha)	Available P(kg/Ha)	Available K(kg/Ha)	Available Ca(mg/kg)	Available Mg(mg/kg)	Available S(mg/kg)
T1	99.941[c]	100.464[c]	168.414	384[c]	400.8[b]	22.247[ab]
T2	153.560[b]	137.110[a]	190.70[9]	316[d]	249.6[d]	22.035[b]
T3	130.888[b]	118.250[b]	203.800	300[d]	458.4[b]	10.570[e]
T4	130.976[b]	73.633[d]	164.600	404[c]	307.2[cd]	20.905[c]
T5	62.888[d]	112.918[b]	113.000	300[d]	331.2[c]	16.225[d]
T6	249.098	94.842c	163.456	480[b]	403.2[b]	22.780[a]
T7	127.467[bc]	146.317[a]	197.000	400[c]	458.4[b]	9.330[f]
T8	97.469[c]	97.552[c]	182.314	592[a]	604.8[a]	4.735[g]
SE(m)	10.66	3.49	21.9	205.7	21.7	0.203
CD	3.32	1.9	NS	36.3	6	0.58

3.3 Crop Phenology, Biomass and Yield

3.3.1 Effect of Hydrogel

A significant reduction in number of days to 50% flowering (22.2 days) was noted in treatment involving 3kg/ha of hydrogel (Table 10). This suggests that improved soil moisture regime by optimal rate of application of hydrogel resulted in the fastest onset of reproductive phase (Kumar et al., 2020). Maximum dry matter production (35.3g) was recorded in treatment T3. Marques et al. (2025) noted that super absorbent polymers increase plant biomass by enhancing water use efficiency and nitrogen retention in the soil. Higher dry matter and accelerated flowering in T3 did not reflect on the economic yield of crop. This discrepancy is likely attributable to the dynamics of source-sink partitioning, where biomass may not effectively get diverted to the harvested organs. Benefits from hydrogel are most effective under moisture stress conditions, rather than under irrigated conditions (Elnamas et al., 2025).

Table 10. Growth and yield of chilli at various doses of hydrogel

Treatments	Days to 50% flowering	Plant height (cm)	Plant biomass (g)	Number of fruits/ plant	Fruit length (cm)	Fruit weight (g)	Fruit yield (g/plant)	Dry matter accumulation (g)
T1	24.4[b]	49.4	80.6	26.6	5.340	1.740	46.860	20.5[b]
T2	37.6[a]	52.6	75.8	17.2	5.110	1.496	25.298	22.9[b]
T3	22.2[b]	49.0	74.0	30.4	5.486	1.370	41.508	35.3[a]
T4	26.2[b]	51.0	77.4	23.8	5.480	1.464	32.876	23.9[b]
SE(m)	2.382	2.594	7.28	4.89	0.404	0.141	7	1.33
CD	2.06	NS	NS	NS	NS	NS	NS	1.54

3.3.2 Effect of Humic Acid

The treatment involving synthetic humic acid at 10kg/ha resulted in the early onset of 50% flowering (19 days) and highest fruit yield (43.55 g $plant^{-1}$) which are in conformity with the findings of Vinod et al. (2024). Auxin-like activity of humic substances stimulates cell division thereby increasing fruit set and yield. In another study, it was revealed that the growth promoting action of humic acid is dependent on its dosage. Optimal yields were observed at intermediate concentrations of humic acid beyond which vegetative growth may compete with reproductive growth (Atiyeh et al., 2002).

The plant biomass (157.8 g) and number of fruits per plant (32.6) were higher in treatment T5. The reason behind is that organic functional groups present in plant-derived humic acid favour sustained release of nutrients from soil and promotes vegetative development and reproductive partitioning. Similar findings were reported by Piccolo et al. (1997). By means of increased cation exchange capacity of soil, humic acid ensures nutrient availability during critical crop growth stages (Khaled & Fawy, 2011).

Table 11. Growth and yield of chilli under humic acid treatments

Treatments	Days to 50% flowering	Plant height (cm)	Plant biomass (g)	Number of fruits/ plant	Fruit length (cm)	Fruit weight (g)	Fruit yield (g/plant)	Dry matter accumulation (g)
T1	22.6^{cd}	64.4	143.8^{a}	26.6^{ab}	5.18	1.508	39.570^{a}	28.66
T2	23.6^{bc}	58.0	81.4^{b}	21.2^{abc}	4.76	1.178	31.766^{ab}	31.20
T3	26.2^{ab}	51.6	74.0^{b}	12.8^{cd}	4.44	1.320	16.620^{bc}	21.88
T4	19.4^{d}	56.0	86.6^{b}	29.2^{a}	5.00	1.576	43.548^{a}	30.50
T5	22.0^{cd}	50.2	157.8^{a}	32.6^{a}	5.74	1.278	40.550^{a}	23.50
T6	29.0^{a}	61.0	61.0^{b}	3.0^{d}	5.04	1.350	4.180^{c}	19.96
T7	23.6^{bc}	60.2	77.6^{b}	15.2^{bc}	4.94	1.326	20.284^{bc}	24.20
T8	26.2^{ab}	45.6	84.8^{b}	11.2^{cd}	5.40	1.368	15.132^{bc}	16.90
SE(m)	1.17	4.68	14.19	4.22	0.314	0.18	6.49	5.54
CD	1.39	NS	4.85	2.64	NS	NS	3.28	NS

3.3.3 Effect of Biochar

The highly porous structure of biochar creates favourable environment for better root development leading to higher dry matter production (33g) and fruit yield (67.4g/plant) in treatment T6. Biochar helps in better nutrient mobilization by increasing soil microbial activity as suggested by Suriya et al. (2025). It also helps to maintain soil moisture during the critical flowering stage and thereby increases fruit yield (Afaf et al., 2023). In contrast, biochar application did not provide significant variation with respect to days to 50% flowering, plant height, plant biomass, fruit length, and fruit weight. The above-mentioned parameters are primarily governed by the genetic potential of plant and soil moisture availability, rather than the soil carbon enhancement by biochar (Paneque et al., 2016).

Table 12. Growth and yield parameters of chilli influenced by biochar treatments

Treatments	Days to 50% flowering	Plant height (cm)	Plant biomass (g)	Number of fruits/ plant	Fruit length (cm)	Fruit weight (g)	Fruit yield (g/plant)	Dry matter accumulation (g)
T1	21.6	56.4	81.4	21.4^{e}	4.84	1.280	27.980^{b}	27.5^{ab}
T2	23.6	51.4	75.0	30.2^{cde}	4.56	1.188	35.868^{b}	25.1^{abc}
T3	23.8	45.2	79.2	36.2^{bcd}	4.78	1.126	40.510^{b}	25.7^{abc}
T4	21.2	52.6	79.0	46.2^{ab}	5.36	1.404	65.692^{a}	25.0^{abc}
T5	20.0	53.2	93.6	40.4^{bc}	4.82	1.102	46.308^{ab}	20.3^{bcd}
T6	22.6	48.2	62.8	55.8^{a}	3.68	1.226	67.464^{a}	33.0^{a}
T7	24.6	54.8	57.8	25.0^{de}	5.24	1.150	30.260^{b}	17.5^{cd}
T8	24.8	54.8	56.8	29.8^{cde}	4.08	0.920	27.760^{b}	15.1^{d}
SE(m)	1.13	4.15	10.25	3.98	0.53	0.16	7.61	3.36
CD	NS	NS	NS	2.57	NS	NS	3.55	2.36

3.4 Plant Nutrient Uptake

3.4.1 Effect of Hydrogel

Plant nitrogen content increased linearly with increase in hydrogel dose. The highest value (1.372%) was recorded in treatment T4 (Table 14). This is in conformity with the findings of Syvertsen and Dunlop (2004) who reported that hydrogel act as a chemical reservoir and reduces the leaching of nitrate and ammonium ions. This ensures sustained availability of nitrogen during the vegetative growth phase. Content of phosphorus (0.145%) and potassium (0.476%) in the plant were maximum in treatment T3. A slight reduction in these nutrients was noted at the highest hydrogel dose. Qin et al., (2024) reported that hydrogels facilitate nutrient diffusion and at higher doses it may cause dilution effect leading to reduced nutrient uptake efficiency. This suggests the relevance of optimal moisture to nutrient ratio in nutrient uptake. This trend is also observed in case of calcium (8633.2 mg/kg) and sulphur (330.12 mg/kg) which were maximum in treatment T2. Magnesium content in plant was maximum in T4 (6020 mg/kg). This may be due to superabsorbent polymer mediated increase in the bioavailability of divalent cations as suggested by Hu et al., (2021).

Table 13. Effect of hydrogel on plant nutrient uptake

Treatments	Total N (%)	Total P (%)	Total K (%)	Total Ca (mg/kg)	Total Mg (mg/kg)	Total S (mg/kg)
T1	0.762^{d}	0.149^{a}	0.474^{a}	6443^{b}	4540^{b}	170.792^{bc}
T2	0.902^{c}	0.114^{b}	0.200^{b}	8633.2^{a}	4640^{b}	330.120^{a}
T3	1.092^{b}	0.145^{a}	0.476^{a}	6840.8^{b}	5760^{a}	232.104^{ab}
T4	1.372^{a}	0.115^{b}	0.217^{b}	6458.8^{b}	6020^{a}	67.988^{c}
SE(m)	0.015	0.008	0.036	149.437	249.098	44.314
CD	0.164214	0.119925	0.2544	16.39	21.16	8.92

3.4.2 Effect of Humic Acid

Nitrogen content (1.394%) was maximum in treatment T6 involving plant derived humic acid (Table 14), suggesting that plant derived humic acid (PDHA) helps in the slow release of nitrogen and thus enhances nitrogen use efficiency (Khattak and Anwar, 2025). Maximum concentration of phosphorus (0.611%) was observed in T8 which received a combination of plant derived and synthetic humic acid. Many studies reported that the synergistic effect of organic acids in humic fractions help in solubilizing fixed phosphorus from the soil, making it available for plant uptake (Xiong et al., 2023). Meanwhile, the highest potassium content (0.539%) was observed in treatment involving synthetic humic acid @ 15 kg ha^{-1} (T4), indicating increased permeability of plant membranes by humic substances facilitating K^{+} ion transport (da Silva et al., 2021).

Uptake of secondary nutrients also varied significantly among the treatments. Maximum plant calcium content (10574.0 mg/kg) was recorded in treatment T4. This may be attributed to humus- cation complex formation helping in preventing soil nutrient leaching. Action of humic acid as a carrier, increasing the cell membrane permeability might also have led to this increased nutrient uptake. Research findings of Paul & Datta, (2023) revealed that humic substances trigger H^{+}-ATPase activity in the plasma membrane by creating an electrochemical gradient which favors nutrient uptake. The highest magnesium (7340 mg/kg) and sulphur (269.560 mg/kg) content were recorded in treatments T7 and T6 respectively, which is likely attributed to the bio stimulant property of humic acid. Humic acid increases the cation exchange capacity of soil which prevents the leaching of Mg^{2+} and SO_4^{2-} ions, making them more bioavailable in the root depletion zone (Yang et al., 2021).

Table 14. Plant nutrient uptake under humic acid treatments

Treatment	Total N (%)	Total P (%)	Total K (%)	Total Ca (mg/kg)	Total Mg (mg/kg)	Total S (mg/kg)
T1	0.907^{cd}	0.104^{e}	0.268^{d}	7393.6^{d}	5760^{cd}	128.484^{de}
T2	0.420^{e}	0.321^{b}	0.256^{de}	6532.8^{e}	5060^{d}	210.52^{abc}
T3	0.879^{d}	0.182^{cd}	0.451^{b}	7235.6^{d}	6340^{bc}	143.6cde
T4	1.002^{c}	0.087^{e}	0.539^{a}	10574^{a}	5040^{d}	192.2^{bcd}
T5	0.980^{c}	0.248^{bc}	0.222^{de}	7425.6^{d}	6900^{ab}	165.39^{bcd}
T6	1.394^{a}	0.116^{de}	0.286^{d}	4713.6^{f}	7220^{a}	269.560^{a}
T7	1.165^{b}	0.221^{c}	0.201^{e}	9604.4^{b}	7340^{a}	89.368^{e}
T8	1.310^{a}	0.611^{a}	0.366^{c}	9072.0^{c}	5100^{d}	236.54^{a}b
SE(m)	0.035	0.027	0.023	88.193	250.35	25.678
CD	0.24	0.21	0.19	12.09	20.38	6.52

3.4.3 Effect of Biochar

The total plant nitrogen content varied significantly among the treatments involving biochar, which ranged from 0.689% to 1.450% (Table 15). Higher nitrogen content was noted in T6, as higher surface area of hardwood biochar decreases volatilization and leaching loss of ammoniacal nitrogen. Khan et al., (2023) identified that the functional groups in wood-derived biochar enhanced the retention of nitrogenous fertilizers and hence improved nitrogen use efficiency. Phosphorus content in plant was maximum (0.390%) at higher dose of biochar in T5. A study by Zhang et al., (2025) reported that biochar helps in regulation of phosphorus fractions in the rhizosphere by enhancing microbial phosphatase activity. Biochar derived from wood serves as an excellent source of available potassium (Zong et al., 2016). In the present study, higher content of potassium (0.464%) in treatment T8 may be due to the direct release of potassium from the biochar ash and due to the increase in cation exchange capacity of the soil. Treatments containing hardwood biochar were better than those with rice husk biochar with respect to the uptake of secondary nutrients (Table 14). Maximum calcium content (9422.4 mg/kg) in plants was recorded in T7 and magnesium was highest (6620 mg/kg) in treatment T6. Gondek et al., (2019) observed that biochar increased the effective cation exchange capacity of soil, which facilitated the retention of divalent cations like Ca^{2+} and Mg $^{2+}$ on the exchange sites and hence prevent their displacement by H^+ ions. In terms of sulphur, a linear increase was observed with biochar dosage, peaking at 540.48 mg/kg in T8. This is due to the highly porous nature of biochar which facilitates better microbial oxidation of organic sulphur into plant-available forms (Cheah et al., 2014).

Table 15. Nutrient content in plant as influenced by biochar treatments

Treatments	Total N (%)	Total P (%)	Total K (%)	Total Ca (mg/kg)	Total Mg (mg/kg)	Total S (mg/kg)
T1	0.689^{e}	0.358^{a}	0.287^{b}	8459.6^{b}	5160^{c}	125.768^{b}
T2	1.014^{cd}	0.200^{bc}	0.272^{bc}	7926.8^{c}	4300^{d}	204.344^{b}
T3	1.182^{bc}	0.106^{cd}	0.300^{b}	7252.8^{f}	4520^{cd}	132.672^{b}
T4	1.159^{bcd}	0.114^{cd}	0.243^{bc}	8627.6^{b}	4440^{d}	223.560^{b}
T5	1.271^{ab}	0.390^{a}	0.258^{bc}	7551.6d^{e}	6300^{ab}	179.456^{b}
T6	1.450^{a}	0.260^{ab}	0.200^{c}	7800.4^{cd}	6620^{a}	467.480^{a}
T7	1.232^{b}	0.330^{ab}	0.298^{b}	9422.4^{a}	6740^{a}	201.280^{b}
T8	0.963^{d}	0.028^{d}	0.464^{a}	7385.6^{ef}	5880^{b}	540.480^{a}
SE(m)	0.07	0.046	0.028	95.546	223.607	41.154
CD	0.34	0.27	0.21	12.5	19.26	8.26

3.5 Fruit Nutrient Content

3.5.1 Effect of Hydrogel

Maximum concentration of nitrogen (1.428%), phosphorus (0.692%) and potassium (0.505%) in the fruit were observed in the treatment involving hydrogel @ 3kg/ha (Table 16), which indicates that moderate dose of hydrogel facilitates efficient translocation of these nutrients from the vegetative parts to the reproductive organs. Marques et al., (2025) reported that constant supply of moisture by hydrogel prevents the trapping of nutrients in soil and effectively reduces nitrate leaching. Phosphorus and potassium content in fruits were lower at higher doses of hydrogel. Solubility of phosphates and diffusion rates of potassium are adversely affected by the localized saturation of nutrients at higher dosage as reported by Mikhailidi et al., (2024). Higher content of calcium (6359.2 mg/kg) and magnesium (5120 mg/kg) in the fruit were recorded in treatments T3 and T4 respectively. Treatment T3 contributed in better translocation of calcium and magnesium to the fruit. Previous studies revealed that hydrogel improves the partitioning of calcium toward the developing fruits and also impart higher cation exchange capacity in soil, improving the uptake of divalent cations like Mg^{2+} (de Moura, 2024). Variation of sulphur content in fruit was non-significant across the treatments.

Table 16. Effect of hydrogel on nutrient content in fruits

Treatments	Total N (%)	Total P (%)	Total K (%)	Total Ca (mg/kg)	Total Mg (mg/kg)	Total S (mg/kg)
T1	0.885^{c}	0.212^{c}	0.322^{c}	5413.2^{b}	3840^{b}	500.917
T2	1.198^{b}	0.170^{c}	0.270^{d}	4465.6^{d}	3860^{b}	420.974
T3	1.428^{a}	0.692^{a}	0.505^{a}	6359.2^{a}	4700^{a}	551.897
T4	1.406^{a}	0.572^{b}	0.360^{b}	4835.2^{c}	5120^{a}	574.390
SE(m)	0.033	0.033	0.006	81.58	199.123	109.294
CD	0.24	0.24	0.10	12.11	18.92	NS

3.5.2 Effect of Humic Acid

Results indicated that nitrogen content in the fruit was highest (1.434%) in treatment T5, which was on par with T6 (1.428%). Fan et al., (2025) reported that humic acid increases the activity of enzymes like nitrate reductase that facilitates the conversion of inorganic nitrogen into organic forms required for fruit development. Total phosphorus (0.633%) and potassium (0.952%) in fruit were maximum in T3 and T5 respectively. This may be due to the formation of humic-metal-phosphate complexes that reduce phosphorus fixation by iron and aluminium oxides in acidic soils (Wang et al., 1995). The data also revealed that fruit calcium content was maximum (8292.8 mg/kg) in T5 and that of magnesium (7992.8 mg/kg) was highest in T6, suggesting that higher dosage of PDHA facilitated better mobility of calcium and magnesium to the fruits. Treatment T8 exhibited highest sulphur content in the fruit (659.176 mg/kg) which indicates a synergistic effect between PDHA and synthetic HA at higher doses. In a study by Aguiar et al., (2013), it was reported that humic acids enhance the uptake of sulphate ions by activating the sulphur transporter genes in the roots.

Table 17. Fruit nutrient content under variable rates of humic acids

Treatments	Total N (%)	Total P (%)	Total K (%)	Total Ca (mg/kg)	Total Mg (mg/kg)	Total S (mg/kg)
T1	0.896^{d}	0.171^{d}	0.360^{d}	5356.4^{d}	5056.4^{d}	395.421^{c}
T2	0.930^{d}	0.338^{bc}	0.284^{e}	4468.4^{e}	4552.4^{d}	176.375^{d}
T3	1.081^{c}	0.633^{a}	0.515^{c}	5356.0^{d}	6066.4^{c}	503.579^{b}
T4	1.215^{b}	0.343^{bc}	0.395^{d}	6936.0^{b}	6636^{bc}	196.852^{d}
T5	1.434^{a}	0.292^{c}	0.952^{a}	8292.8^{a}	6891.6^{b}	380.520^{c}
T6	1.428^{a}	0.444^{b}	0.901^{a}	7191.6^{b}	7992.8^{a}	372.520^{c}
T7	1.344^{a}	0.441^{b}	0.577^{bc}	6541.6^{c}	6241.6^{c}	252.920^{d}
T8	1.170^{bc}	0.386^{bc}	0.636^{b}	6606.4^{c}	4912.0^{d}	659.176^{a}
SE(m)	0.03	0.037	0.024	98.46	206.6	34.3
CD	0.23	0.106	0.19	12.78	18.5	7.55

3.5.3 Effect of Biochar

Among the treatments, T6 recorded the highest value of nitrogen content (1.562%) in fruit (Table 18). Zheng et al., (2013) observed that biochar increases the retention and uptake of mineral nitrogen in solanaceous crops. Highest phosphorus (0.978%) and potassium content (0.903%) in treatments T7 and T8 respectively suggests that biochar serves as a catalyst for releasing the fixed phosphorus. The ash fraction of biochar is a direct source of exchangeable potassium (Khan et al., 2013). Significantly higher amount of calcium and magnesium were noted in treatments involving hardwood biochar. This matches with the reports of Piash et al., (2021) that wood-based biochar has more stable carbon matrix and denser functional groups (carboxyl and phenolic), which increase the cation exchange capacity of soil, allowing the soil to hold more Ca^{2+} and Mg^{2+} ions for plant uptake. The maximum sulphur content (477.97 mg/kg) in treatment receiving hardwood biochar at higher dose can be justified with the results of Dotaniya et al., (2024), who reported that biochar application stimulates the activity of arylsulfatase enzymes that facilitate mineralization of organic sulphur into plant-available sulphate forms.

Table 18. Effect of biochar on fruit nutrient content

Treatments	Total N (%)	Total P (%)	Total K (%)	Total Ca (mg/kg)	Total Mg (mg/kg)	Total S (mg/kg)
T1	0.885^{e}	0.255^{b}	0.208^{e}	7252^{b}	4160^{c}	141.78^{d}
T2	0.902^{e}	0.339^{b}	0.488^{cd}	6623.2^{c}	3940^{c}	137.908^{d}
T3	1.064^{d}	0.234^{b}	0.639^{bc}	7440^{b}	3920^{c}	272^{b}
T4	1.389^{b}	0.267^{b}	0.346^{de}	5493.2^{d}	5020^{b}	118.208^{d}
T5	1.254^{bc}	0.209^{b}	0.378^{de}	6378.4^{c}	5760^{ab}	302.823^{b}
T6	1.562^{a}	0.268^{b}	0.347^{de}	7231.6^{b}	5420^{a}	201.136^{c}
T7	1.310^{bc}	0.978^{a}	0.758^{ab}	8472.8^{a}	6140^{a}	477.97^{a}
T8	1.193^{cd}	0.33^{b}	0.903^{a}	8258^{a}	4680^{c}	253.56^{bc}
SE(m)	0.053	0.154	0.064	90.23	264.5	19.6
CD	0.29	0.50	0.32	12.23	20.9	5.7

4. Conclusion

Results of the study revealed that the application of soil amendments such as hydrogel, humic acid and biochar significantly enhances most of the physical and chemical properties of sandy loam soils. In nutrient poor soils, these amendments provide a sustainable pathway for its rejuvenation and hence enhances agricultural productivity. Low to moderate application of hydrogel (2-3 kg/ha) effectively reduces soil bulk density and also improves water-stable aggregates. While it significantly improves available nitrogen and calcium at lower doses, higher concentrations can sequester divalent cations, potentially reducing their availability to the plant. Both synthetic and plant-derived humic acids improved soil structure and soil organic carbon content. Meanwhile, synthetic humic acid at 15 kg/ha was particularly effective in promoting early flowering and achieving the highest fruit yield (43.55 g/plant), attributed to its bio stimulant activity. Hardwood biochar outperformed rice husk biochar in improving soil porosity, water-holding capacity, and long-term carbon sequestration. Specifically, hardwood biochar at the rate of 5-10 t/ha significantly improved nitrogen and phosphorus availability while enhancing the uptake of secondary nutrients. Hence, a moderate dose of hydrogel, synthetic humic acid and hardwood biochar can lead to resilient and sustainable agriculture by facilitating better soil nutrient dynamics and crop response. The high cost of hydrogel (about Rs. 1,200/kg) and rice husk biochar (Rs. 900/kg) makes it difficult for farmers to afford them. However, the high crop output offsets this initial expense. Moving forward, we can expect the development of more cost-effective production methods for these amendments.

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Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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