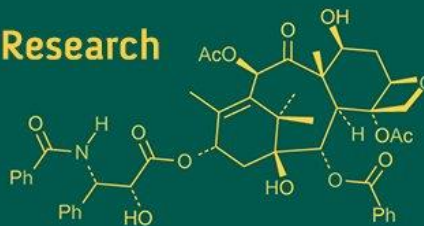


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Soil amendments on nutrient status of upland rice (*Oryza sativa* L.)

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Abstract

Field study was conducted at Instructional Farm, College of Agriculture, Vellanikkara to elucidate the impact of soil amendments in nutrient status. The experimental design followed was factorial CRD with three replications. Treatments consisted of 5 soil amendments viz., M₁-silica @ 100 kg ha⁻¹, M₂-Biochar @ 5 t ha⁻¹ (rice hull ash), M₃-hydrogel @ 2.5 kg ha⁻¹ (Pusa hydrogel), M₄-25% of additional potassium of the recommended dose(RD) of potassium (45 kg ha⁻¹) at two splits, M₅-control without amendment and 3 moisture stress levels viz., I₁-50% field capacity (FC) (at all growth stages), I₂-stress at maximum tillering (MT) and panicle initiation (PI) stage, I₃-no moisture stress. Soil amendments had significant influence on nutrient content of soil. Biochar application recorded higher available nitrogen and phosphorus contents, while hydrogel treatment resulted in maximum available potassium content and improved soil reaction. The amendments also contributed to maintaining favourable pH and EC conditions without causing salinity problems. Thus soil amendments had a positive influence on nutrient content of soil than without any soil amendment applied plots.

Keywords: Silica, nutrient uptake, hydrogel, biochar, soil nutrient status

Introduction

Soil fertility and nutrient availability are major determinants of crop productivity and sustainable agricultural development. However, continuous cultivation, imbalanced fertilizer application, depletion of soil organic matter, and environmental degradation have resulted in declining soil health and nutrient deficiencies in many agricultural soils. Intensive agricultural practices often reduce microbial activity, nutrient use efficiency, and soil structural stability, thereby negatively affecting crop growth and productivity. In this context, improving soil nutrient status through suitable soil amendments has become an important strategy for sustaining agricultural production and maintaining environmental quality.

Soil amendments such as farmyard manure, compost, biochar, gypsum, silicon, crop residues, and mineral fertilizers are widely used to improve soil physical, chemical, and biological properties. Organic amendments enhance soil organic carbon, microbial activity, water holding capacity, and cation exchange capacity, thereby improving nutrient availability and retention in soil. Lehmann and Joseph (2015) ^[9] reported that biochar application significantly improved soil nutrient retention, microbial activity, and nutrient use efficiency in degraded soils. Similarly, Agegnehu *et al.* (2017) ^[3] observed that integrated application of compost and inorganic fertilizers increased soil organic carbon, available nitrogen, phosphorus, and potassium while improving crop productivity.

Several studies have demonstrated the beneficial effects of organic amendments on soil nutrient dynamics. Adekiya *et al.* (2020) ^[2] reported that application of poultry manure and biochar significantly increased soil organic matter, available phosphorus, exchangeable potassium, and total nitrogen content compared to untreated soil. Likewise, Blanco-Canqui (2021) ^[5] emphasized that organic amendments improve nutrient cycling, soil aggregation, and microbial biomass, thereby enhancing long-term soil fertility and sustainability.

Biochar has gained considerable attention due to its potential to improve nutrient retention and reduce nutrient losses through leaching. According to Liu *et al.* (2022) ^[12], biochar amendment increased soil pH, cation exchange capacity, and availability of essential nutrients, resulting in improved nutrient uptake and crop performance. In addition, silicon amendments have been reported to enhance nutrient availability and alleviate abiotic stresses

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in crops. Ahire *et al.* (2021)^[4] stated that silicon application improves nutrient balance, root growth, and physiological efficiency under stress conditions, thereby contributing to better soil-plant interactions.

Integrated use of organic and inorganic amendments has also been found effective in maintaining soil fertility and sustaining crop productivity. Zhang *et al.* (2023)^[20] reported that combined application of organic manure and mineral fertilizers significantly enhanced soil nutrient status, microbial diversity, and nutrient use efficiency compared to sole fertilizer application. Similarly, Sharma *et al.* (2022)^[16] observed improvements in available N, P, and K content and increased microbial activity following the application of vermicompost and biofertilizers in agricultural soils.

In recent years, emphasis on sustainable and climate-resilient agriculture has increased interest in eco-friendly soil management practices. Soil amendments not only improve nutrient availability and soil fertility but also contribute to carbon sequestration, reduced greenhouse gas emissions, and improved soil biodiversity. Therefore, understanding the effect of different soil amendments on nutrient status of soil is essential for developing sustainable nutrient management strategies and improving long-term agricultural productivity.

Hence, the present study was undertaken to evaluate the influence of different soil amendments on the nutrient status of soil and their role in enhancing soil fertility and sustainable crop production.

Materials and Methods

A field experiment was conducted at Instructional Farm, College of Agriculture, Vellanikkara, Kerala Agricultural University, during late *Rabi* 2024 with the objective to know how soil amendments influenced nutrient status soil. Rice variety *Uma* (medium duration) was used for the study. The experimental design followed was CRD which was replicated thrice. Treatments consisted of 5 soil amendments viz., M₁-silica @ 100 kg ha⁻¹, M₂-Biochar @ 5 t ha⁻¹ (rice hull ash), M₃-hydrogel @ 2.5 kg ha⁻¹ (Pusa hydrogel), M₄-25% additional potassium of the recommended dose of potassium (45 kg ha⁻¹) at two splits, M₅-control without amendment. All treatments except biochar treatment liming was done followed by application of Farm Yard Manure (FYM) before three days of sowing and the soil was mixed thoroughly. Biochar was applied one week after application of FYM then soil was thoroughly mixed. Hydrogel capsules were applied after one week of crop emergence it was kept at the base of rice seedlings. Nitrogen (Urea-46% N) was applied in field as three splits one at basal dose during field preparation and other at MT and PI stage. Phosphorus was applied as rock phosphate (P₂O₅-20%) as basal dose. Potassium was applied at one week after emergence of crop and at tillering stage with muriate of potassium as the source (60% KCl). Soil pH before sowing was 4.83 and EC was 0.33dS. Nutrient analysis was done using standard procedure. The statistical data analysis was done using GRAPES KAU version 1.1.0.

Results and Discussion

The nutrient content in soil was significantly influenced by the incorporation of soil amendments. Soil organic carbon is also closely associated with nutrient availability and nutrient cycling. Organic matter acts as a reservoir of essential nutrients such as nitrogen, phosphorus and sulphur, and its

decomposition gradually releases nutrients for plant uptake. Estimation of organic carbon therefore helps in assessing the nutrient supplying capacity of soil and the effectiveness of soil amendments such as biochar, compost and crop residues.

In addition, soil organic carbon improves cation exchange capacity and buffering capacity of soil, which helps retain nutrients and reduces nutrient losses through leaching. It also supports beneficial microbial populations that are involved in decomposition, mineralization and other biochemical processes essential for maintaining soil fertility. Organic carbon content of soil was significantly influenced by different soil amendments. Among the treatments, control without any amendments (M₅) recorded the highest organic carbon content (1.71%), followed by Pusa hydrogel (M₃) with 1.29% and 25% additional potassium than recommended KAU POP (M₄) with 1.23%. Silica application (M₁) recorded an organic carbon content of 0.84%, whereas the lowest value was observed in biochar treatment (M₂) with 0.75%.

The higher organic carbon content observed in the control treatment might be due to lower mineralization and reduced microbial decomposition under the absence of external amendments. Application of Pusa hydrogel also maintained relatively higher organic carbon, which could be attributed to improved soil moisture retention and favourable conditions for accumulation of organic residues in soil. Similar findings were reported by Narjary *et al.* (2012)^[13], who observed improved soil physical properties and enhanced carbon conservation with hydrogel application under moisture stress conditions.

The increase in organic carbon with additional potassium application may be associated with improved crop growth and greater root biomass contribution to soil organic matter. Potassium enhances photosynthetic activity and biomass production, thereby increasing residue return to soil. Similar observations were reported by Zorb *et al.* (2014)^[21], who stated that potassium nutrition plays an important role in carbon assimilation and translocation in plants.

Lower organic carbon content under silica and biochar treatments may be due to enhanced microbial activity and faster decomposition of organic matter. Although biochar is generally known to improve soil carbon status, its effect depends on the type of feedstock, application rate and soil conditions. Similar variable responses of soil organic carbon following biochar application were reported by Lehmann and Joseph (2015)^[9].

Soil pH was influenced by different soil amendments and varied from 6.56 to 6.96. Among the treatments, Pusa hydrogel (M₃) recorded the highest pH (6.96), followed by 25% additional potassium than recommended KAU POP (M₄) with 6.85 and biochar (M₂) with 6.71. Silica application (M₁) recorded a pH of 6.64, whereas the lowest pH was observed in control without any amendments (M₅) with 6.56.

The increase in soil pH under hydrogel and biochar treatments might be attributed to improved soil buffering capacity and retention of basic cations in the soil solution. Biochar is known to contain alkaline functional groups and ash components that can neutralize soil acidity and improve soil chemical properties. Similar findings were reported by Lehmann *et al.* (2011)^[10], who observed an increase in soil pH following biochar application. Higher pH under potassium application may be due to improved nutrient

balance and reduced acidic effects in the rhizosphere. Comparable results were also reported by Havlin *et al.* (2014) [18], who stated that balanced fertilization helps maintain favorable soil reaction.

Electrical conductivity of soil was significantly affected by soil amendments and ranged from 57 to 141 $\mu\text{S cm}^{-1}$. The highest EC was recorded in biochar treatment (M2) with 141 $\mu\text{S cm}^{-1}$, followed by silica application (M1) and Pusa hydrogel (M3), both recording 90 $\mu\text{S cm}^{-1}$. The treatment receiving 25% additional potassium than recommended KAU POP (M4) recorded an EC of 71 $\mu\text{S cm}^{-1}$, while the lowest EC was observed in control without amendments (M5) with 57 $\mu\text{S cm}^{-1}$.

The higher EC observed under biochar application could be due to the release of soluble salts and mineral ash content present in biochar. Biochar amendments generally increase ionic concentration in soil solution, thereby enhancing EC. Similar observations were reported by Yuan and Xu (2011) [18], who noted that biochar application increased soil EC due to the presence of soluble inorganic constituents. Increased EC under silica and hydrogel treatments may also be associated with enhanced nutrient retention and moisture conservation in soil.

Available nitrogen content of soil was significantly influenced by different soil amendment treatments. Among the treatments, biochar @ 5 t ha^{-1} (M2) recorded the highest available nitrogen content (308 kg ha^{-1}), followed by hydrogel @ 2.5 kg ha^{-1} (M3) (296 kg ha^{-1}), 25% additional potash (M4) (284 kg ha^{-1}) and silica @ 100 kg ha^{-1} (M1) (272 kg ha^{-1}). The lowest available nitrogen content was observed in control treatment (248 kg ha^{-1}). The increase in available nitrogen under amended treatments indicated the beneficial influence of soil amendments on nutrient retention, mineralization and soil biological activity.

Higher available nitrogen under biochar application may be attributed to improved soil organic carbon status, enhanced microbial activity and greater retention of ammoniacal nitrogen due to the high surface area and cation exchange capacity of biochar. Biochar minimizes nitrogen losses through leaching and volatilization and promotes gradual nutrient release in soil. Similar findings were reported by Purakayastha *et al.* (2024) [15], who observed that biochar application significantly improved nutrient availability and soil fertility through enhanced nutrient retention and microbial processes in agricultural soils.

Likewise, Ullah *et al.* (2023) [17] reported that partial substitution of urea with biochar significantly improved soil enzyme activity, nitrogen uptake and nitrogen availability in double-cropping rice systems due to enhanced nitrification processes and improved microbial population in soil.

Hydrogel application also recorded comparatively higher available nitrogen than control. This may be due to the superior water holding capacity of hydrogel, which maintained favourable soil moisture conditions for microbial decomposition and nitrogen mineralization. Improved moisture retention reduces nitrogen loss through leaching and enhances nutrient use efficiency in the rhizosphere. Recent studies on superabsorbent polymers in rice soils demonstrated that hydrogels improved nutrient retention and nitrogen use efficiency under moisture stress conditions.

Application of additional potash maintained higher available nitrogen compared to control. Potassium plays a crucial role in nitrogen metabolism, protein synthesis and nutrient uptake efficiency. Improved potassium nutrition enhances

root growth and nutrient absorption, thereby contributing to improved residual soil nitrogen status.

Silica-treated plots also showed comparatively higher available nitrogen than control. Silicon amendments improve root development, nutrient uptake efficiency and soil biochemical properties under stress conditions. Silicon also enhances microbial activity and nutrient mobilization in rice soils. Yuan *et al.* (2024) [19] reported that silicon-calcium fertilizer improved soil health, nutrient availability and rice productivity by enhancing soil chemical and biological properties.

The overall results indicated that soil amendments such as biochar, hydrogel and silica positively influenced soil nitrogen status by improving nutrient retention, microbial activity and soil moisture conditions compared to untreated control.

Available phosphorus and potassium content of soil was markedly influenced by different soil amendments. Among the treatments, biochar @ 5 t ha^{-1} (M2) recorded the highest available phosphorus content (45.45 kg ha^{-1}), whereas the lowest phosphorus availability was observed under silica application (9 kg ha^{-1}). The increase in phosphorus availability under biochar treatment may be attributed to the release of phosphorus from biochar ash fraction, reduction in phosphorus fixation and improvement in microbial activity and soil adsorption characteristics. Biochar possesses high surface area and cation exchange capacity, which enhances nutrient retention and gradual nutrient release in soil. Similar findings were reported by Gupta *et al.* (2024) [7], who observed significantly higher phosphorus availability in biochar-amended soils due to improved phosphorus desorption and reduced fixation.

Recent studies also demonstrated that continuous application of biochar increased active and bioavailable phosphorus fractions in paddy soils by improving phosphorus dynamics and reducing the proportion of stable phosphorus forms unavailable to plants. Gao *et al.* (2024) [6] reported that biochar significantly enhanced active phosphorus content and phosphorus saturation in rice soils, thereby improving phosphorus availability throughout crop growth stages.

Hydrogel @ 2.5 kg ha^{-1} (M3) and control (M5) recorded intermediate phosphorus values (13.5 kg ha^{-1}), while application of 25% additional potash (M4) recorded 15.75 kg ha^{-1} . Improved phosphorus availability under hydrogel treatment may be due to enhanced soil moisture retention, which facilitates nutrient diffusion, microbial activity and mineralization processes in the rhizosphere. Better moisture availability improves solubilization and movement of phosphorus towards plant roots, thereby increasing available phosphorus in soil.

Available potassium content also varied considerably among treatments. Highest available potassium was recorded in hydrogel application (M3) (522.5 kg ha^{-1}), followed by biochar application (M2) (485.1 kg ha^{-1}) and additional potash treatment (M4) (451 kg ha^{-1}). The lowest potassium availability was recorded in control (375.1 kg ha^{-1}). Higher potassium availability under hydrogel treatment could be due to the water holding capacity of hydrogel, which minimizes potassium leaching losses and maintains nutrient availability in the root zone for a longer period. Hydrogels also improve nutrient use efficiency by gradual release of absorbed nutrients under adequate soil moisture conditions.

Biochar application substantially improved available potassium content owing to its high mineral ash content and greater cation exchange capacity, which enhances potassium retention in soil. Biochar acts as a slow-release source of potassium and reduces nutrient losses through leaching. Similar observations were reported in long-term paddy field studies where biochar application significantly improved nutrient availability, including exchangeable potassium, and enhanced soil fertility status.

The comparatively higher potassium availability in silica-treated plots than control may be attributed to beneficial interactions between silicon and potassium nutrition. Silicon amendments improve nutrient mobilization, reduce nutrient losses and enhance nutrient uptake efficiency under stress conditions. Studies on rice husk biochar rich in silicon also reported improved availability of potassium and associated nutrients in soil systems.

Table 1: Effect of soil amendments on soil nutrient status

Treatments	pH	OC	EC ($\mu\text{S cm}^{-1}$)	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})
M ₁ -Silica @ 100 kg ha ⁻¹	6.64	0.84	90	272	9	383.9
M ₂ -Biochar @ 5 t ha ⁻¹	6.71	0.75	141	308	45.45	485.1
M ₃ -Hydrogel @ 2.5 kg ha ⁻¹	6.96	1.29	90	296	13.5	522.5
M ₄ -25% of additional potash that KAU POP	6.85	1.23	71	284	15.75	451
M ₅ -Control	6.56	1.71	57	248	13.5	375.1
Mean	6.74	1.16	89.80	281.60	19.44	443.52
CD	0.16	0.40	31.93	22.81	14.57	63.44

Note: OC-Organic carbon, EC-Electrical conductivity, KAU POP-Kerala Agricultural University Package of Practices.

Conclusion

The present study demonstrated that application of soil amendments significantly influenced soil chemical properties and nutrient availability after crop harvest. Among the different treatments, biochar @ 5 t ha⁻¹ and hydrogel @ 2.5 kg ha⁻¹ proved more effective in improving soil fertility parameters compared to silica application, additional potash and control. Biochar application recorded higher available nitrogen and phosphorus contents, while hydrogel treatment resulted in maximum available potassium content and improved soil reaction. The amendments also contributed to maintaining favourable pH and EC conditions without causing salinity problems. Improvement in soil nutrient status under biochar and hydrogel treatments may be attributed to enhanced nutrient retention, improved soil moisture conservation, greater microbial activity and reduced nutrient losses. Silica application also showed positive influence on soil fertility compared to control, particularly in maintaining nutrient availability under stress conditions. Overall, the findings indicated that incorporation of suitable soil amendments can improve soil health and nutrient dynamics, thereby contributing to sustainable crop production and efficient nutrient management in rice-based systems.

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Declarations

Ethics Approval and Consent to Participate: Not applicable.

Consent for Publication: The manuscript has been approved by all authors

Competing Interests: No competing interest

Author contribution

All authors contributed to the study conception and design. All authors have approved and concept and gave valuable insights on materials and methods. Material preparation, data collection and analysis were performed by A. The first draft of the manuscript was written by A and B. All authors

commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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