Enhancing soil nutrient availability through surface application of biochar and organic amendments with different liming materials in laterite soils of Kerala, India

ABSTRACT

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| --- |
| **Aims:** A 12-week column incubation study was conducted under laboratory conditions using the southern laterite soils (AEU-8) of Kerala, India, to evaluate the effect of co-application of biochar and other organic amendments with liming materials on soil nutrient availability. **Place and Duration of Study:** Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani, Thiruvananthapuram, Kerala Agricultural University, India between February 2023 and April 2023.**Methodology:** The 17 treatments studied included farmyard manure (FYM) at 20 t ha-1, humic acid (HA) at 10 kg ha-1, poultry manure (PM) at 1 t ha-1 and coconut frond biochar (CFB) at 10 t ha-1 each in combination with lime, dolomite, calcium silicate (CS) or phosphogypsum (PG) at lime requirement (LR) and a soil alone control.**Results:** Results indicated that co-application of organic amendments and liming materials significantly increased organic carbon (by 38.10 to 85.71%) and available nitrogen (30.43 to 95.65%), phosphorus (14.54 to 67.49%), potassium (4.77 to 109.87%) and sulphur (35.51 to 78.81%), compared to the control. CFB at 10 t ha-1 with dolomite as per LR, PM at 1 t ha-1 with lime as per LR, FYM at 20 t ha-1 with CS as per LR, CFB at 10 t ha-1 with lime as per LR and CFB at 10 t ha-1 with PG as LR, recorded significantly highest values for soil organic carbon and available nitrogen, phosphorous, potassium and sulphur, respectively, compared to other treatment combinations. Available Fe, Mn, Zn and Cu were recorded significantly highest for the control treatment, compared to other treatment combinations.**Conclusion:** In general, application of CFB at 10 t ha-1 with different liming materials (lime, dolomite, PG or CS as per LR) significantly improved soil nutrient availability while reducing excess micronutrient accumulation, thereby enhancing soil health and fertility. Therefore, co-application of biochar with different liming materials, integrated with the recommended dose of fertilizers, can be recommended to farmers as a sustainable practice to improve soil health and enhance crop yields. |

*Keywords: available nutrients, coconut frond biochar, calcium silicate, lime, laterite soil, phosphogypsum.*

1. INTRODUCTION

The laterite soils of Kerala are formed through intense weathering and leaching processes under high rainfall and temperature conditions, leading to the accumulation of iron (Fe) and aluminium oxides while depleting silica and other minerals. These soils are acidic, exhibit low plant nutrient levels and a low cation exchange capacity (CEC), resulting in weak retention of essential bases applied through fertilizers or soil amendments. These soils are relatively infertile and require careful management strategies to enhance fertility and achieve optimal crop yields (Rajasekharan *et al*. 2014).

 Liming is a fundamental and effective management practice for reducing soil acidity. It improves soil quality by lowering exchangeable aluminium (Al) concentrations, increasing CEC, and improving base saturation, thereby promoting better soil fertility and plant growth (Islam *et al*. 2021). However, in acidic laterite soils, the sole application of lime may not be sufficient to restore fertility. By raising the soil pH and CEC and reducing the availability of hazardous metals in severely worn soils, organic amendments with high liming capacity can also help to improve soil productivity and crop yield. Studies have shown that the combined application of organic amendments and liming materials enhances soil physical, chemical and biological properties, thus contributing to improved nutrient cycling and crop performance. Tuber yield of cassava was increased by 13.9 t ha-1 when poultry manure and lime were applied together, compared to the control (Anyaegbu *et al*. 2010). Application of cow manure with dolomite is reported to improve plant biomass weight of maize, compared to the control (Suntoro *et al*. 2018).

Organic amendments like biochar with high alkalinity can also help to improve soil productivity. The application of biochar increases CEC and soil pH, enhances the supply and uptake of nutrients, reduces nutrient leaching and nitrogen (N) volatilization losses, and ultimately improves nutrient availability in soils (Banu *et al*. 2023). Biochar produced from coconut frond and coconut husk significantly increased the mineralizable nitrogen, available phosphorus, and available potassium content of soil (Jabin and Rani 2020). Co-application of paddy straw biochar and ganajeevamruth increased the average pod number by 88.63% and pod weight by 83.18% compared to biochar alone (Anusha *et al*. 2025). Combined application of citrus tree biochar and PG at a rate of 10 Mg ha-1 each, resulted in improved grain yield of maize plants by 43 per cent (Mahmoud *et al*. 2018).

Therefore, the present study aims to evaluate the effectiveness of organic amendments, including biochar in combination with liming materials, in enhancing the available nutrient content of the laterite soils of Kerala.

2. material and methods

A column incubation study was conducted under laboratory conditions using the southern laterite soils (AEU-8) of Kerala at College of Agriculture, Vellayani, Thiruvananthapuram, Kerala to investigate the effect of combined application of CFB at 10 t ha-1, FYM at 20 t ha-1, HA at 10 kg ha-1 or PM at 1 t ha-1 with lime, dolomite, PG or CS as per LR, in different combinations, on available nutrient status of the soil.

**2.1 Soil sampling**

Site of laterite soil sampling for the incubation study was located at 80 25ʹ36ʺ North latitude and 760 59ʹ 17ʺ East longitude at an altitude of 29 m above MSL, at College of Agriculture Vellayani, Thiruvananthapuram, Kerala. The soil was classified as loamy, kaolinitic, isohyperthermic, Typic Kandiustult, belonging to the Vellayani series. The fresh soil samples were collected in polythene bags, labelled and transported to the laboratory, where they were air-dried, ground and sieved through a 2 mm mesh for further analysis.

**2.2 Collection of ameliorants**

Phosphogypsum (PG) was obtained from the Fertilizers and Chemicals Travancore Ltd. (FACT), calcium silicate from Astrra Chemicals, Tamil Nadu, humic acid from Rohini Agro Science Ltd. in Ernakulam, and poultry manure and farmyard manure were obtained from College of Agriculture, Vellayani. Biochar was produced by the method of slow pyrolysis from coconut frond at the department of Soil Science and Agricultural Chemistry, College of Agriculture Vellayani.

**2.3 Characterization of Soil and organic amendments**

The soil samples were analyzed for organic carbon and available nutrients (N, P, K, S, Fe, Mn, Zn and Cu) using standard procedures. Soil organic carbon (OC) was estimated using Walkley and Black titration method (Walkley and Black 1934) and available nitrogen (N) by alkaline permanganate method (Subbiah and Asija 1956). Available phosphorous (P) and sulphur (S) were extracted using Bray No. 1 reagent (Jackson 1973) and 0.15 % CaCl2 method (Massoumi and Cornfield 1963), respectively, and quantified with spectrophotometer. Available potassium (K) was extracted with neutral 1N ammonium acetate and quantified using flame photometer (Jackson 1973). Available Fe, Mn, Zn and Cu were extracted using 0.1 M HCl and subsequently quantified using atomic absorption spectrophotometer (Sims and Johnson 1991).

All the organic amendments were analyzed for total C, N, P, K, S, Fe, Mn, Zn and Cu (Table 1). Total C and N were determined using CHNS analyzer (Byers *et al*. 1978). Samples were digested with nitric- perchloric (9:4) acid mixture and P, K, S, Fe, Mn, Zn and Cu were quantified by using atomic absorption spectrophotometer (Jackson 1973).

**2.4 Setting up of the incubation experiment**

 Polyvinyl chloride (PVC) columns of 60 cm length and 10 cm diameter were used for the study. Soil from the selected site was packed into the columns to achieve the same bulk density as in the field (1.53, 1.6 and 1.61 Mg m-3 at 0-15, 15-30 and 30-60 cm depth of soil, respectively). The treatments were uniformly mixed into the top 15 cm of soil on a weight basis. The soil columns were maintained at field capacity.

The treatments were T1: FYM @ 20 t ha-1 + lime as per LR (0.93 g) **,** T2: HA @ 10 kg ha-1 + lime as per LR**,** T3: PM @ 1 t ha-1 + lime as per LR**,** T4: CFB @ 10 t ha-1 + lime as per LR**,** T5: FYM @ 20 t ha-1 + dolomite as per LR (0.92 g)**,** T6: HA @ 10 kg ha-1 + dolomite as per LR**,** T7: PM @ 1 t ha-1 + dolomite as per LR**,** T8: CFB @ 10 t ha-1 + dolomite as per LR**,** T9: FYM @ 20 t ha-1 + PG as per LR (1.97 g)**,** T10: HA @ 10 kg ha-1 + PG as per LR**,** T11: PM @1 t ha-1 + PG as per LR, T12: CFB @ 10 t ha-1 + PG as per LR**,** T13: FYM @ 20 t ha-1 + CS as per LR (1.97 g)**,** T14: HA @ 10 kg ha-1 + CS as per LR**,** T15: PM @ 1 t ha-1 + CS as per LR and T16: CFB @ 10 t ha-1 + CS as per LRand T17: Soil alone. Each treatment had two replications, arranged in a completely randomized design. Leaching was conducted three times in the prepared soil columns at 4, 8, and 12 weeks of incubation by adding twice the pore volume of water.

Soil sampling was conducted at the end of the 12-week incubation study. Surface soil samples were collected and air dried. After air-drying, the soil samples were ground and passed through a 2 mm sieve. Soil samples were analysed for organic carbon and available N, P, K, S, Fe, Mn, Zn, and Cu using the standard procedures mentioned above.

Table 1: Chemical properties of organic amendments

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sl. No.** | **Properties** | **FYM** | **HA** | **PM** | **CFB** |
|  | Total C (%) | 23.42 | 24.51 | 20.81 | 41.11 |
|  | Total N (%) | 1.07 | 0.85 | 2.97 | 0.44 |
|  | C: N ratio | 21.78 | 28.79 | 7.01 | 93.43 |
|  | Total P (%) | 0.61 | 0.72 | 0.32 | 0.95 |
|  | Total K (%) | 0.70 | 0.20 | 0.74 | 0.91 |
|  | Total S (%) | 0.09 | 0.21 | 0.11 | 0.25 |
|  | Total Fe (mg kg-1) | 813.30 | 35.80 | 361.71 | 73.17 |
|  | Total Mn (mg kg-1) | 94.50 | 27.70 | 63.10 | 58.00 |
|  | Total Zn (mg kg-1) | 40.12 | 39.80 | 13.80 | 25.43 |
|  | Total Cu (mg kg-1) | 5.13 | 3.69 | 3.54 | 2.98 |

3. results

The organic carbon content of the soil collected from the experimental site was 1.03%, and the available N, P, K, S, Fe, Mn, Zn, and Cu contents were 74.17, 33.70, 74.80, 9.5, 11.64, 14.91, 4.29, and 4.26 mg kg⁻¹, respectively.

**3.1 Available nutrients**

The results pertaining to the effect of different treatments on the soil nutrient status after column incubation study are given in Table 2 and 3.

**3.1.1 Organic carbon**

 Organic carbon content of soil after incubation was highest (1.56 %) for the treatment CFB at 10 t ha-1 with dolomite as per LR (T8) which was on par with the treatments receiving CFB at 10 t ha-1 with CS (T16) (1.43 %), lime (T4) (1.40 %) or PG (T12) (1.40 %) as per LR and significantly higher than FYM at 20 t ha-1, HA at 10 kg ha-1 and PM at 1 t ha-1, along with lime, dolomite, PG or CS as per LR. Lower values for OC were observed for the treatment receiving PM at 1 t ha-1 with lime (T3) (1.16 %), dolomite (T7) (1.20 %), PG (T11) (1.20 %) or CS (T15) (1.20 %) as per LR. The control treatment recorded significantly lowest value (0.84 per cent).

**3.1.2 Available nitrogen**

Available N was higher for all the treatments receiving PM at 1 t ha-1 followed by FYM at 20 t ha-1, HA at 10 kg ha-1, CFB at 10 t ha-1 with lime, dolomite, PG or CS as per LR. PM at 1 t ha-1 with lime as per LR (T3) gave the highest value of 126 mg kg-1 which was on par with treatments receiving PM at 1 t ha-1 with dolomite (T7) (123.2 mg kg-1), CS (T15) (123.2 mg kg-1) or PG (T11) (120.4 mg kg-1) as per LR and FYM at 20 t ha-1 with PG as per LR (T9) (117.6 mg kg-1). CFB at 10 t ha-1 with lime as per LR (T4) registered the lowest value (84.0 mg kg-1) for available N which was on par with CFB at 10 t ha-1 along with dolomite (T8) (89.6 mg kg-1), PG (T12) (89.6 mg kg-1) or CS (T16) (92.4 mg kg-1) as per LR compared to other treatments except the control.

**3.1.3 Available phosphorous**

 Available P content of soil after incubation showed the maximum value for treatments supplied with CS or PG, respectively, as per LR along with FYM at 20 t ha-1 or HA at 10 kg ha-1or PM at 1 t ha-1 or CFB at 10 t ha-1. The highest value of 53.25 mg kg-1 for available P was obtained for FYM at 20 t ha-1 with CS as per LR (T13) which was on par with CFB at 10 t ha-1 with CS as per LR (T16) (51.50 mg kg-1). The control treatment recorded significantly lowest value (31.79 mg kg-1).

**3.1.4 Available potassium**

 Available K content increased from 73.25 mg kg-1 in T17 (control) to 153.75 mg kg-1 in T4 (CFB at 10 t ha-1 + lime as per LR). All the treatments receiving CFB gave significantly higher values for available K, compared to other treatment combinations. CFB at 10 t ha-1 with lime as per LR gave significantly highest value (153.75 mg kg-1) for available K followed by CFB at 10 t ha-1 with CS as per LR (147.00 mg kg-1) which was on par with CFB at 10 t ha-1 with PG (146.25 mg kg-1).

**3.1.5 Available sulphur**

 Combined application of organic and inorganic amendments significantly increased the available S content of soil with the treatment receiving PG as per LR registering the highest values followed by dolomite, lime and CS as per LR along with FYM at 20 t ha-1 or HA at 10 kg ha-1 or PM at 1 t ha-1 or CFB at 10 t ha-1. T12 receiving CFB at 10 t ha-1 with PG as per LR registered the highest value (13.50 mg kg-1) for available S and it was on par with all other treatments receiving PG as per LR applied along with HA at 10 kg ha-1 (T10) (13.15 mg kg-1) or PM at 1 t ha-1 (T11) (13.00 mg kg-1) or FYM at 20 t ha-1 (T9) (12.99 mg kg-1). The control treatment recorded significantly lowest value (7.55 mg kg-1) for available S.

**3.1.6 Available iron**

 Treatment application had significant effect on available Fe content of soil. Control treatment recorded significantly highest available Fe content of 13.89 mg kg-1, while treatments supplied with either PG or CS per LR along with different organic amendments (FYM at 20 t ha-1, HA at 10 kg ha-1, PM at 1 t ha-1 or CFB at 20 t ha-1) recorded lower values and the lowest value (8.46 mg kg-1) was observed for CFB at 10 t ha-1 with PG as per LR (T12) which was on par with all the other treatments receiving PG or CS as per LR and CFB at 10 t ha-1 applied along with dolomite as per LR.

**3.1.7 Available manganese**

 The data revealed that available manganese content of soil varied from 5.02 mg kg-1 in T12 (CFB at 10 t ha-1 + PG as per LR) to 10.43 mg kg-1 in T17 (control). Lower values for available Mn content were observed for treatments supplied with PG or CS as per LR, respectively, with different organic amendments (FYM at 20 t ha-1, HA at 10 kg ha-1, PM at 1 t ha-1 and CFB at 20 t ha-1) compared to the other treatments. Significantly lowest value (5.02 mg kg-1) for available Mn was recorded by T12 (CFB at 10 t ha-1 + PG as per LR) which was on par with T11 (5.24 mg kg-1) and T10 (5.32 mg kg-1) receiving PM at 1 t ha-1 and HA at 10 kg ha-1, respectively, along with PG as per LR. Available Mn content of CFB at 10 t ha-1 with CS as per LR (5.54 mg kg-1) was on par with FYM at 20 t ha-1 with CS as per LR (5.82 mg kg-1) and they were significantly lower than all other treatments except T10, T11 and T12.

**3.1.8 Available zinc**

 Control recorded significantly highest value for available Zn content followed by dolomite, lime, PG or CS as per LR along with different organic amendments (FYM at 20 t ha-1, HA at 10 kg ha-1, PM at 1 t ha-1 and CFB at 20 t ha-1). Generally, application of HA at10 kg ha-1 with inorganic amendments (lime, dolomite, PG and CS as per LR) resulted in lower values for available Zn content compared to other organic amendments. Significantly lowest value of 2.48 mg kg-1 was recorded by T10 (HA at 10 kg ha-1 + PG as per LR) and T16(CFB at 10 t ha-1 + CS as per LR) which was on par with T11 (PM at 1 t ha-1 + PG as per LR) (2.54 mg kg-1) and T9 (FYM at 20 t ha-1 + PG as per LR) (2.63 mg kg-1).

**3.1.9 Available copper**

The effect of different treatments on available Cu content of soil after incubation was significant. The control treatment (2.99 mg kg-1) gave significantly highest value for available Cu content followed by lime, dolomite, PG or CS as per LR along with FYM at 20 t ha-1 or HA at 10 kg ha-1 or PM at 1 t ha-1 or CFB at 10 t ha-1. Significantly lowest value for available Cu was for PM at 1 t ha-1 with CS as per LR (T15) (1.73 mg kg-1) followed by FYM at 20 t ha-1 with CS as per LR (T13) (1.89 mg kg-1) which was on par with all the other treatments receiving CS and PG as per LR along with FYM at 20 t ha-1, HA at 10 kg ha-1, PM at 1 t ha-1 or CFB at 10 t ha-1.

Table 2: Effect of treatments on available nutrient status of leached soil after the incubation period

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Treatments** | **OC (%)** | **N****(mg kg-1)** | **P****(mg kg-1)** | **K****(mg kg-1)** | **S****(mg kg-1)** |
| T1 | 1.23 ± 0.03 de | 109.2 ± 3.96 a | 42.92 ± 0.35 efgh | 113.75 ± 1.77 f | 11.80 ± 0.35 cd |
| T2 | 1.25 ± 0.014 cde | 95.2 ± 0.0 efg | 41.29 ± 0.06 fghi | 107.50 ± 3.54 g | 11.35 ± 0.35 def |
| T3 | 1.16 ± 0.01 e | 126.0 ± 3.96 a | 40.21 ± 0.30 ghij | 127.50 ± 0.71 d | 11.98 ± 0.035 c |
| T4 | 1.40 ± 0.12 abc | 84.0 ± 0.0 h | 37.67 ± 0.71 jk | 153.75 ± 1.06 a | 11.15 ± 0.14 efg |
| T5 | 1.24 ± 0.15 cde | 109.2 ± 3.96 bc | 43.17 ± 0.71 efgh | 126.25 ± 1.06 de | 11.50 ± 0.07 cde |
| T6 | 1.23 ± 0.03 de | 98.0 ± 3.96 defg | 38.50 ± 1.88 ijk | 114.25 ± 0.35 f | 12.58 ± 0.18 b |
| T7 | 1.20 ± 0.01 e | 123.2 ± 7.92 a | 36.42 ± 2.00 k | 123.25 ± 0.35 e | 12.55 ± 0.7 b |
| T8 | 1.56 ± 0.06 a | 89.6 ± 0.0 gh | 39.75 ± 0.24 hijk | 138.50 ± 1.41 c | 11.43 ± 0.25 cde |
| T9 | 1.22 ± 0.15 e | 117.6 ± 0.0 ab | 46.00 ± 0.35 de | 128.00 ± 0.71 d | 12.99 ± 0.17 ab |
| T10 | 1.29 ± 0.11 bcde | 100.8 ± 0.0 cdef | 46.00 ± 0.59 de | 108.75 ± 1.77 g | 13.15 ± 0.28 a |
| T11 | 1.20 ± 0.11 e | 120.4 ± 11.88 a | 43.75 ± 1.53 defg | 76.75 ± 1.77 i | 13.00 ± 0.07 ab |
| T12 | 1.40 ± 0.01 abcd | 89.6 ± 0.0 gh | 49.54 ± 0.88 bc | 126.25 ± 0.35 de | 13.50 ± 0.07 a |
| T13 | 1.30 ± 0.13 bcde | 106.4 ± 0.0 cd | 53.25 ± 5.90 a | 146.25 ± 1.77 b | 10.23 ± 0.25 i |
| T14 | 1.26 ± 0.07 bcde | 103.6 ± 3.96 cde | 46.79 ± 0.06 cd | 123.25 ± 1.06 e | 10.55 ± 0.14 hi |
| T15 | 1.20 ± 0.01 e | 123.2 ± 0.0 a | 44.16 ± 0.83 def | 93.25 ± 1.77 h | 10.63 ± 0.18 ghi |
| T16 | 1.43 ± 0.1 ab | 92.4 ± 3.96 fgh | 51.50 ± 0.11 ab | 147.00 ± 0.71 b | 10.80 ± 0.21 fgh |
| T17 | 0.84 ± 0.03 f | 64.4 ± 3.96 i | 31.79 ± 0.06 l | 73.25 ± 1.77 j | 7.55 ± 0.14 j |
| SEm± | 0.058 | 3.04  | 1.187 | 1.064 | 0.185 |
| CD (0.05) | 0.173 | 9.06 | 3.541 | 3.175 | 0.552 |

Table 3: Effect of treatments on micronutrient content (mg kg-1) of leached soil after the incubation period

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Treatments** | **Fe** | **Mn** | **Zn** | **Cu** |
| T1 | 12.51 ± 0.14 bc | 8.12 ± 1.05 bc | 3.00 ± 0.01 def | 2.30±0.01cd |
| T2 | 11.88 ± 0.59 bcd | 8.16 ± 0.01 bc | 2.99 ± 0.03 def | 2.38±0.04c |
| T3 | 12.34 ±1.69 bcd | 8.49 ± 0.53 b | 3.17 ± 0.07 cd | 2.56±0.07b |
| T4 | 11.56 ±1.56 bcde  | 8.07 ± 0.04 bc | 3.34 ± 0.01 bc | 2.41±0.22c |
| T5 | 13.41 ± 0 .60 ab  | 7.06 ± 0.33 bcd | 3.54 ± 0.05 ab | 2.38±0.04c |
| T6 | 10.74 ± 1.42 cdef | 7.24 ± 0.18 bcd | 2.80 ± 0.01 fgh | 2.02±0.01f |
| T7 | 10.54 ± 0.60 def | 7.30 ± 0.35 bcd | 3.28 ± 0.0 4c | 2.29±0.01cd |
| T8 | 9.08 ± 0.15 fg | 6.87 ± 0.19 cde | 3.18 ± 0.26 cd | 2.18±0.04de |
| T9 | 9.13 ± 1.43 fg | 6.27 ± 1.16 def | 2.63 ± 0.09 hij | 1.97±0.07f |
| T10 | 8.94 ± 0.01 fg | 5.32 ± 0.98 f | 2.48 ± 0.09 j | 1.90±0.13f |
| T11 | 8.86 ± 0.40 fg | 5.24 ± 0.30 f | 2.54 ± 0.01 ij | 1.91±0.06f |
| T12 | 8.46 ± 0.01 g | 5.02 ± 0.04ef | 3.06 ± 0.07 de | 2.04±0.01ef |
| T13 | 8.94 ± 0.59 fg | 5.82 ± 0.04 def | 2.92 ± 0.01 efg | 1.89±0.01f |
| T14 | 9.10 ± 0.10 fg | 6.46 ± 0.61 def | 2.90 ± 0.07 efg | 1.95±0.05f |
| T15 | 9.41 ± 1.75 fg  | 6.91 ± 0.50 cde | 2.74 ± 0.22 ghi | 1.94±0.06f |
| T16 | 9.74 ± 0.05 efg | 5.54± 1.92 ef | 2.48 ± 0.04 j | 1.73±0.01g |
| T17 | 13.89 ± 0.04 a | 10.43 ± 0.02 a | 3.56 ± 0.06 a | 2.99±0.02a |
| SEm± | 0.643 | 0.498 | 0.068 | 0.051 |
| CD (0.05) | 1.918 | 1.485 | 0.204 | 0.154 |

***Note: The data are mean ± standard deviation***

T1: FYM at 20 t ha-1 + lime as per LR, T2: HA at 10 kg ha-1 + lime as per LR, T3: PM at 1 t ha-1 + lime as per LR, T4: CFB at 10 t ha-1 + lime as per LR, T5: FYM at 20 t ha-1 + dolomite as per LR, T6: HA at 10 kg ha-1 + dolomite as per LR, T7: PM at 1 t ha-1 + dolomite as per LR, T8: CFB at 10 t ha-1 + dolomite as per LR, T9: FYM at 20 t ha-1 + PG as per LR, T10: HA at 10 kg ha-1 + PG as per LR, T11: PM at 1 t ha-1 + PG as per LR, T12: CFB at 10 t ha-1 + PG as per LR, T13: FYM at 20 t ha-1 + CS as per LR, T14: HA at 10 kg ha-1 + CS as per LR, T15: PM at 1 t ha-1 + CS as per LR, T16: CFB at 10 t ha-1 + CS as per LR and T17: Control (soil alone)

4. Discussion

**4.1 Soil organic carbon**

 Significantly highest values for soil organic carbon (SOC) content were obtained for the treatments receiving CFB at 10 t ha-1 with different liming treatments. This could be due to the higher persistence of biochar in the soil compared to any other form of organic matter, making it a prime candidate for carbon sequestration. The primary reason for the higher stability of biochar in soils is its resistance to microbial decomposition (Liang *et al.* 2008) which is due to the presence of aromatic structures (Downie *et al.* 2009). Application of coconut husk and shell biochar at 10 t ha-1 gave OC values significantly higher than FYM at 10 t ha-1 (Rajkumar 2019). Corncob biochar application at 4.5 Mg ha−1 yr−1 significantly enhanced SOC content, particulate OC content and total soil OC content compared to the no-biochar control (Shi *et al*. 2021).

Liming can increase SOC due to higher carbon inputs resulting from increased productivity. It is influenced by several factors, including the promotion of soil biological activity by liming, which facilitates the breakdown of organic matter and increases its availability in the soil. Furthermore, liming improves soil structure by enhancing the stability of clay formations and bonds between clay and organic matter, leading to increased physical and physicochemical protection for SOC (Paradelo *et al*. 2015). Combined application of lime with NPK fertilizers increased SOC concentrations by 4 to 11 per cent, compared to fertilizer alone (Simek *et al*. 1999)

**4.2 Available nitrogen**

Available N was significantly highest for all the treatments receiving PM at 1 t ha-1 followed by FYM at 20 t ha-1, HA at 10 kg ha-1, CFB at 10 t ha-1 with lime or dolomite or PG or CS as per LR. It is attributed to the high N content and lowest C: N ratio of PM. After applying poultry waste, mineralization happens relatively quickly. About 69 per cent of the organic N present in poultry litter, when mixed into a sandy loam soil, was mineralized within 140 days (Bitzer and Sims 1988). Lowest value for available N was observed in treatments receiving CFB might be due to the high C: N ratio of biochar leads to immobilisation of N. Plant based biochar consist of various N containing structures which get condensed and form heterocyclic N aromatic structures during pyrolysis. Consequently, the residual N in biochar is largely found as recalcitrant heterocyclic N rather than available N (Cao and Harris, 2010) which reduce the mineralization rate of N. Biochar applied also decreased N leaching by 11 per cent (Laird *et al*. 2010).

Application of PM at 5 Mg ha-1 with NPK resulted in higher available N levels compared to the treatment receiving 3.5 Mg ha-1 cotton stick biochar with NPK and 20 Mg ha−1 FYM with NPK (Ahmad *et al*. 2021). Applying PM at a rate of 5 t ha-1 increased the total N content of soil by 26 per cent compared to the treatment receiving 25 t ha-1 wood biochar (Adekiya *et al*. 2019).

**4.3 Available phosphorous**

Available P content of soil after incubation showed the maximum value for treatments receiving CS as per LR followed by PG as per LR with FYM at 20 t ha-1 or HA at 10 kg ha-1or PM at 1 t ha-1 or CFB at 10 t ha-1. Incorporation of silicon (Si) in soil can significantly increase the population of functional microorganisms involved in P cycle. Application of Si increased the numbers of ammoniated and phosphate-solubilizing bacteria and rates of urease and acid phosphatase activity in paddy soil by 73.12, 130.36, 28.12 and 20.15 per cent compared to the control (Liang *et al*. 2021). Thus, Si helps to promote the mineralization of organic matter and leads to increased availability of P in soil. The high solubility of PG facilitates the release of P in soil and improves the microbial activity and population in soil resulting in higher P availability (Caires and Guimaraes 2018).

Lower values for available P were observed in treatments receiving dolomite as per LR along with different organic amendments. Reduction in soil P levels following lime application might arise from the formation of Ca-P precipitates and could be due to an increase in the proportion of absorbable P species (Barrow 1984). Haynes and Ludecke (1981) reported an increase in Al-bound P fraction under liming. Similar results were also obtained by Mathew (2003) and Bouray *et al*. (2020).

**4.4 Top of FormAvailable potassium**

All the treatments receiving CFB at 10 t ha-1 with lime or CS or PG or dolomite as per LR gave the highest values for available K compared to other treatment combinations. High K content in biochar and its ability to adsorb a considerable amount of K from the soil result in the reduction of leaching losses of K, thereby contributing to increased K availability in the soil. Soil incorporation of 3.5 Mg ha−1 biochar with NPK (80:45:30 kg ha−1) resulted in the highest available K followed by 5 Mg ha−1 PM with NPK and 10 Mg ha−1 FYM with NPK (Ahmad *et al*. 2021). Application of biochar was reported to increase the soil available K by 64 per cent, compared to the control (Masto *et al*. 2013).

**4.5 Available sulphur**

Available S content of treatments receiving PG as per LR registered the higher values followed by dolomite, lime and CS as per LR with FYM at 20 t ha-1 or HA at 10 kg ha-1 or PM at 1 t ha-1 or CFB at 10 t ha-1. CFB at 10 t ha-1 with PG as per LR recorded the highest value for available S and it was on par with all other treatments receiving PG as per LR. It might be due to the high S content and high solubility of PG. Application of gypsum at 250 kg ha-1 and dolomite at 50 per cent LR improved the available S of soil by 0.8 and 4.66 mg kg-1, respectively, compared to the treatment receiving lime at 50 per cent LR (Ananthakumar *et al*. 2019). Available S content of soil was significantly increased by the application of PG (Mathew 2003; Nogueira and Melo 2003).

**4.6 Available iron, manganese, zinc and copper**

The lowest values for available Fe, Mn, Zn and Cu were observed in treatments receiving CS or PG as per LR along with FYM at 20 t ha-1, HA at 10 kg ha-1 or PM at 1 t ha-1 or CFB at 10 t ha-1. The decrease in micronutrient availability in the soil by the application of PG could be due to the ligand exchange reactions facilitated by it. Additionally, the self-liming effect of gypsum raises the pH and decreases the exchangeable Al and Fe in acidic soils (Sumner 1990). Also, gypsum facilitates the precipitation of FeSO₄2- contributing to a decrease in Fe availability in the soil (Alcordo and Rechcigl 1993).

Fe and Mn form precipitates of metal silicate with CS which reduces the availability in soil (Liang *et al*. 2015). Available Fe and Mn content significantly reduced by the application of CS compared to the control (Nagula *et al*. 2016). Micronutrients also form stable complexes with clay and humus that occur in both soil solid and solution phases (Barber 1995). Application of lime and cellulose resulted in the immobilisation of micronutrients into organically complexed and amorphous Fe oxides bound fractions (Saha *et al*. 1999). Application of lime equivalent to 1.5 times exchangeable Al content reduced the available Fe content of soil from 6.95 to 6.83 ppm (Jacob 1992). Exchangeable Fe content decreased from 246.3 to 210.6 ppm by the application of lime at the rate 0.5 to 2 times the exchangeable Al equivalent (Sakeer 1997). Similar results were obtained by Gupta *et al*. (1989) and Devi *et al*. (1996).

**5. Conclusion**

 It may be inferred that the co-application of coconut frond biochar with liming materials (lime, dolomite, calcium silicate or phosphogypsum as per LR) significantly influenced soil nutrient availability in southern laterite soils. The treatment combinations, CFB at 10 t ha-1 with dolomite as per LR, PM at 1 t ha-1 with lime as per LR, FYM at 20 t ha-1 with CS as per LR, CFB at 10 t ha-1 with lime as per LR and CFB at 10 t ha-1 with PG as per LR were superior to other treatment combinations for improving organic carbon and available N, P, K, and S, respectively. Conversely, the control treatment recorded the highest levels of available micronutrients (Fe, Mn, Zn, and Cu), indicating that liming materials and organic amendments helped regulate their excess accumulation. In general, the highest soil available nutrient content was recorded by treatments receiving CFB @ 10 t ha-1 different liming materials. Overall, the study highlights the potential of integrating biochar with liming materials to enhance long term soil fertility, improve organic carbon content and optimize nutrient availability, in laterite soils of Kerala. Further studies are required to assess the effectiveness of organic and inorganic amendments on soil nutrient availability across different soil types and climatic conditions. Additionally, enriching biochar with organic or inorganic nutrients could be explored as a strategy to reduce the quantity of biochar required, while improving its nutrient-supplying capacity and overall effectiveness when applied with inorganic amendments.

Ethical approval

This research has been conducted in an ethical and responsible manner and is in full compliance with all relevant codes of experimentation and legislation.

**Disclaimer (Artificial intelligence)**

The author(s) hereby declares 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.

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