Research Article

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Cocoa pod husk bioachar amendment on potassium dynamics in atropical acidic soil

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Abstract

Biochars are identified for use as an agricultural amendment worldwide. Cocoa Pod Husk (CPH), a waste from cocoa industry,was effectively converted into biochar having high nutrient value. The biochar thus produced was found to have high potassium content, a limiting nutrient in acidic soils. However, it was important to know the different fractions of potassium present in the biochar when used as an amendment in soil. Hence, an incubation experiment was conducted to study the K dynamics in soilsamended with CPH biochar. For this, soils from coconut cultivated fields of CPCRI, Kasaragod were collected and amended with CPH biochar @ 0, 5, 10, 20 and 40 g kg^{-1}.Mixture of soil and biochar and soil alone were kept at 60% field capacity under room temperature conditions for 30 days. Following incubation period, all samples were air-dried and analyzed for different potassium fractions. The results showed that with increasing biochar application rates, all potassium fractions, as well as total potassium, increased. However, when the percentage contribution of each fraction to total potassium was calculated, it became evident that water-extractable K, exchangeable K, and non-exchangeable K fractionsexhibited an upward trend (6.8, 8.9, and 7 % respectively), while the lattice (fixed) potassium fraction declined (22.7 %). Since the availability of potassium is mainly determined by the water-extractable, exchangeable, and non-exchangeable fractions, the amendment of soil with cocoa pod husk biocharenhanced these fractions in the soil, thereby improving potassium availability. The present study clearly indicated that amendment of soil with CPH Biochar @ 5-10 g $kg^{-1}$was beneficial to improve the available status of potassium in a tropical acidic soil.

***Key words*:**Available K; Cocoa pod husk biochar; Exchangeable K; Lattice K; Non-Exchangeable K; Potassium fractions;Water soluble K.

Introduction

Biochar is a black material produced by the process of pyrolysis of plant biomass under oxygen-limited conditions (Lehmann, 2007). Biochar of different originsare largely used as soil amendments due to their unique properties like large surface area, high carbon content and the ability to supply plant nutrients. Also, many studies have proved that biochar could augment the soil pH because of the high content of basic cations like potassium, sodium, calcium and magnesium. Since biochar is a source of carbon, it has the ability to improve the microflora of the soil under various conditions of soil and climate (Biederman and Harpole, 2013). Biocharis known to contain plant-available nutrients, with potassium being the predominant one, regardless of the type of plant biomass used as feedstock. As per reports, the concentration of plant nutrients varies with the type of the feedstock and the pyrolysis temperature toa largeextent, but basic cations are expected to be high compared to others. It is a well-established fact that acidic soils are very much deficient of basic cations *viz.*potassium and calcium, and also have low pH. In such soils, the properties of biochar like high pH and presence of high concentration of basic cations, play a great role in adjusting the pH and supplying the required cations. Hence, as an

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organic amendment,biochar can be a very suitable liming material and source of basic cations.

Potassium is a vital macronutrient essential for the growth and development of all crops. In acidic soil, potassium is the most deficient nutrient and hence its application is unavoidable to get high-yielding and quality products. The increased cost of potassium fertilizers and the lack of native potassium reserves in the soil make it deficient. For this reason, any natural source thatsupplies plant available potassium is encouraged. Most of the plant derivedbiochar are having significant amount of total potassium, but the available fraction of the potassium is the major concern. The availability of potassium in soil is largely governed by the dynamic equilibrium among its different fractions. Therefore, understanding the concentration of each fraction is crucial for evaluating the potassium-supplying capacity of biochar. Najafi-Ghiri and co-workers (2019) reported that corn cobbiochar significantly enhanced potassium availability in calcareous soil, increasing it by 110% compared to its biomass. In soils, potassium predominantly exists in four fractions: water-soluble K, exchangeable K, non-exchangeable K, and lattice (fixed) K, which remain in equilibrium with one another (Oborn*et al*., 2005). Among these, the water-soluble, exchangeable, and non-exchangeable forms are the primary contributors to potassium availability, while lattice K is the least accessible form. However, lattice K hasan important role in maintaining the equilibrium among potassium fractions in soil. In this way, all the four fractions are important to make the potassium available to the plants.

Cocoa is a widely cultivated beverage crop in the world and the economic part is its beanswhich are mainly used in confectionaries. After taking out beans, the left over pod husksare often kept unused and might act as inocula for pod rot diseases of cocoa (Yapo*et al*., 2013). Around 60-70 per cent of the cocoa pod is the pod husk, and this waste, thus generated,can be converted into biocharafter dryingby the process of slow pyrolysis. Converting pod husk waste into biochar is an effective waste management strategy that can also serve as a source of plant nutrients, thereby enhancing soil fertility. Previous studies have reported that cocoa pod husk biochar contains high levels of potassium and calcium (Gopal *et al*., 2024; Munongo*et al*., 2017). Also, Bahrun and co-workers (2018) observed that the application of cocoa pod husk biochar (CPHB) significantly improved soil pH, phosphorus availability, and cation exchange capacity (CEC). Similar results were reported by Neenu*et al.,*(2023). Considering the high total potassium content of cocoa pod husk biochar, the present study was carried outto investigate its various potassium fractions and their role in enhancing the soil potassium availability to plants.

Materials and Methods

Properties ofthe soil and biocharused for the study

Soil samples for the study were collected from coconut cultivation fields of ICAR-CPCRI, Kasaragod. The soils of this region are of lateritic origin with a loamy sand texture. The average annual rainfall in this area is about 3400 mm and is characterized by a warm, humid tropical climate. Samples were collected at a depth of 30 cm, air-dried, and passed through a 2 mm sieve before use in the incubation study. Initial analyses of the soil were carried out for pH, electrical conductivity, organic carbon (Walkley and Black, 1934), total nitrogen, available phosphorus, available potassium, available sodium, and exchangeable calcium and magnesium following standard procedures (Jackson, 1973). DTPA-extractable micronutrients (Fe, Mn, Zn, and Cu) were determined using an atomic absorption spectrophotometer (Lindsay and Norvell, 1978). The physico-chemical properties of the soil are presented in Table 1.

Table 1. Physico-chemical characteristics of the soil used in the study

Parameter	Value
Sand (%)	88.88
Silt (%)	6.13
Clay (%)	4.99
pH	5.62
EC (µS/cm)	33.17
OC (g kg^{-1})	6.80
Total N (%)	0.08
Available P (mg kg^{-1})	26.50
Available K (mg kg^{-1})	30.70
Available Na (mg kg^{-1})	38.80

Exchangeable Ca (mg kg^{-1})	126.7
Exchangeable Mg (mg kg^{-1})	32.0
Available S (mg kg^{-1})	3.30
Available Fe (mg kg^{-1})	16.60
Available Mn(mg kg^{-1})	14.40
Available Zn (mg kg^{-1})	1.90
Available Cu (mg kg^{-1})	0.66

Cocoa pods were brokenopen and the beans inside were separated. The leftover pod husks were dried in sun. The dried husks were then fed into a kiln for conversion into biochar through pyrolysis under oxygen-limited conditions, maintaining a temperature range of 350–500 °C. The resulting biochar was manually crushed, passed through a 2 mm mesh, and used for the incubation study, while a portion was reserved for chemical and microbiological characterization. Chemical properties such as pH and electrical conductivity were determined in a 1:10 biochar-to-water suspension after shaking for one hour in a reciprocating shaker, followed by measurement using a pH/EC meter after 30 minutes of settling (Lee *et al.*, 2013). Total nitrogen was estimated by the Kjeldahl distillation method following sulfuric acid digestion (Bremner*et al.*, 1996). Total elemental concentrations of phosphorus, potassium, sodium, calcium, and magnesium were determined after wet digestion with a diacid mixture (HNOƒ :HClO„ in 9:4 ratio). Total phosphorus was measured using the vanadomolybdate–phosphoric acid yellow colour method with a UV–visible spectrophotometer (Chapman and Pratt, 1961). Total potassium and sodium were estimated with a flame photometer (model CL-378), while calcium and magnesium were quantified using the Versenate titration method (Chang and Bray, 1951). For microbiological characterization, the serial dilution technique combined with surface plating was employed. Plate Count Agar was used, and inoculated petri plates were incubated at 35 ± 2 °C for 24–56 hours. The colonies formed on the agar surface were counted, and results were expressed as colony-forming units (CFU) per gram of biochar. Additionally, CFU values were log € -transformed and expressed as $\log_{10}$ CFU/g. The chemical and microbiological properties of cocoa pod husk biocharare presented in Table 2.

Table 2. Chemical and microbiological properties of CPH biochartaken forstudy

Sl.No	Parameter	Value
1	pH	10.70
2	Electrical Conductivity(mS/cm)	26.60
3	Organic Carbon (%)	13.50
4	Total Nitrogen (%)	1.10
5	Total Phosphorus (%)	0.70
6	Total Potassium (%)	10.90
7	Total Sodium (%)	4.60
8	Total Calcium (%)	2.20
9	Total Magnesium (%)	1.30
10	Total Plate Count (CFU/g)	28 (1.45*)

CFU: Colony Forming Units

*** $\log_{10}$ transformed (in parentheses)**

Incubation Experiment

To investigate the potassium dynamics in soils amended with biochar, a study was carriedout using soils collected from coconut-cultivated fields. CPH biocharwas added to soil at the rate of 0, 5, 10, 20, and 40 g kg^{-1}, designated as B0, B1, B2, B3, and B4, respectively. Both soil and the biocharwere mixed and incubated at 60% field capacity under room temperature conditions for 30 days. The design of the experiment was a Completely Randomized Design (CRD) having five treatments and three replications per treatment. After the incubation period, all control soils and biochar mixed soilswere dried in air and then analyzed for different fractions of potassium.

Potassium Fractions

The major fractions of potassium, namely water-soluble, exchangeable, available, non-exchangeable, lattice (fixed), and total potassium, were analyzed in the soil and soil–biochar mixtures. Water-soluble potassium was extracted by shaking the samples with water in 1:5 ratio for five minutes, followed by estimation using a flame photometer. Exchangeable potassium was determined by shaking the samples with 1 N ammonium acetate (pH 7.0) (1:5 ratio) for five minutes and measuring with a flame photometer (Black, 1965). Available potassium was calculated as the sum of water-soluble and exchangeable potassium. Nitric acid-soluble potassium was estimated by extracting the samples with 1 N HNOƒ in a 1:10 soil-to-acid suspension, boiling for 10 minutes, and then measuring with a flame photometer (Wood and DeTurk, 1941). Non-exchangeable potassium was obtained by subtracting available potassium from 1 N HNOƒ -extractable potassium, while lattice (fixed) potassium was calculated by subtracting 1 N HNOƒ -extractable potassium from total potassium. Total potassium was determined by wet digestion with concentrated HNOƒ and $HClO_4$, followed by measurement using a flame photometer (Pratt, 1982).

Statistical Analysis

The data obtained were statistically analyzedby following the analysis of variance (ANOVA) methodaccording to Gomez and Gomez (1984). A one-way ANOVA was employed, and treatment means were tested for significance using the least significant difference (LSD) at the 5 percent probability level.

Results and Discussion

CPH biochar characteristics

The chemical and microbiological properties of CPH biocharare presented in Table 2. The chemical analysis revealed that CPH biochar had an alkaline pH of 10.7, attributed to its high content of basic cations, a feature common to many biochars (Zhang *et al.*, 2023; Enders *et al.*, 2012). The organic carbon content (13.50 %) was slightly lower than that of other biocharsof different feedstocks, likely due to the effect of the temperature of the pyrolysis process on the feedstock (Cárdenas-Aguiar*et al.,* 2024; Wiedner*et al.*, 2013). Mineral composition analysis indicated a relatively high content of total potassium, suggesting that its application could substantially enhance soil potassium levels. Secondary nutrients such as calcium and magnesium were also present in considerable amounts, contributing to the potential nutrient pool in the soil. The microbiological characterization showed a sparse microflora, as indicated by the low total plate count. This is likely a consequence of high-temperature pyrolysis, which reduced the initial microbial load, and the carbon-rich nature of the biochar, which provided limited support for microbial proliferation.

Effect of CPH biochar addition on Soil K dynamics

The addition of varying levels of potassium through CPH biochar resulted in significant improvements in different soil potassium fractions compared to the control.The behaviour of these fractions in response to CPH biochar application is discussed below.

Water soluble and exchangeable K

The effect of CPH biochar on water-extractable and exchangeable potassium in soil after incubation is presented in Fig. 1. In soil without biochar, only negligible amounts of water-extractable K (8.3 mg kg^{-1}) and very small amount of exchangeable K (21 mg kg^{-1}) were observed. With increasing biochar addition, both water-extractable and exchangeable fractions of potassium increased markedly. Application of 10 g kg^{-1}biochar resulted in a significantly higher exchangeable K content, thereby contributing to the available potassium pool. At higher application rates (20 and 40 g kg^{-1}), there was a substantial improvementin the water-extractable fraction along with exchangeable K. These results indicate that while 10 g kg^{-1} of CPH biochar is sufficient to meet the potassium requirement of soil, higher application rates further enhance both water-extractable and exchangeable fractions. The potassium supplied through CPH biocharwas largely retained in exchange complexes, reducing leaching losses and ensuring sustained availability by maintaining dynamic equilibrium in the soil. Compared to the control, water-extractable K increased by 10.1%, 17%, 49.1% and 69.3% with 5, 10, 20, and 40 g kg^{-1}biochar, respectively, while exchangeable K increased by 13.1%, 23%, 30.8%, and 34.2% under the same treatments. This rise can be attributed to the release of water-soluble and exchangeable potassium from biochar. Similar findings were reported by Fatma and Mahmoud (2025). Since biochar is rich in water-soluble and exchangeable potassium, its incorporation into soil can act as a potent source of K, producing a strong ‘potassium fertilizer effect’ (Hossain *et al.*, 2020).

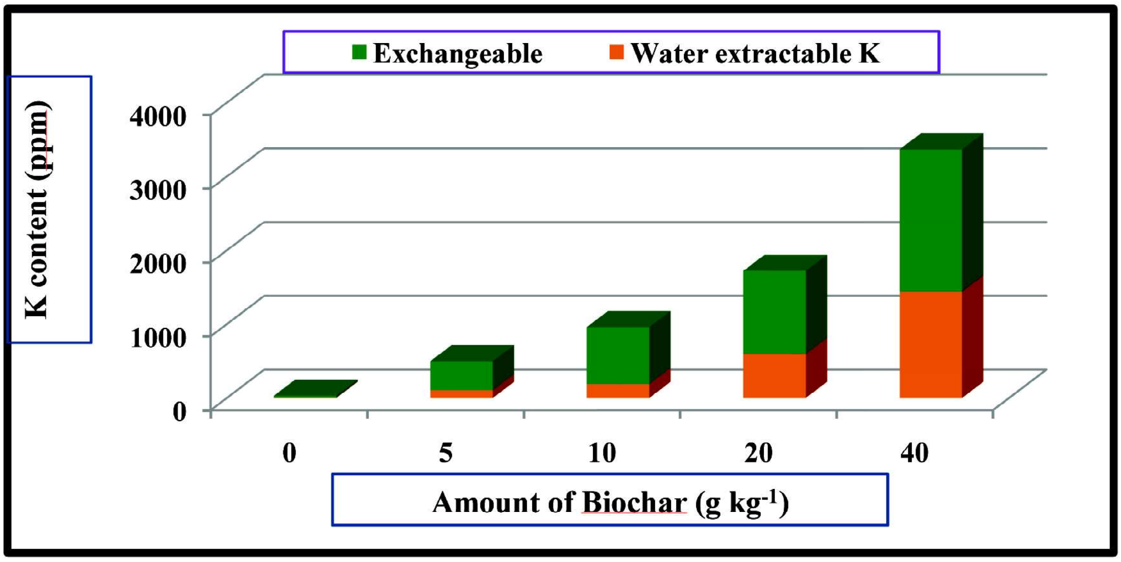

Fig 1. Effect of CPH biochar on water extractable and exchangeable K in the soil

Water-extractable and exchangeable potassium together constitute the available K in soil. In acidic soils, the concentration of available K is generally low; therefore, the application of potassium-supplying materials, either as fertilizers or amendments, is essential. In this context, CPH biochar serves as a valuable source of K to enhance the available potassium pool in soil. Several studies have also reported that biochar application improves water-extractable K in soil (Hossain *et al*., 2020; Safar *et al*., 2019).

Available and non-exchangeable K

The effect of CPH biochar on available and non-exchangeable potassium in soil after incubation is shown in Fig. 2. In the control (without biochar), the available K content was negligible, and the non-exchangeable K fraction was present only in small amounts. With increasing biochar addition, available K increased significantly, while non-exchangeable K also increased at all application rates compared to the control. However, the differences among 5, 10, and 20 g kg^{-1} amendments in non-exchangeable K were not significant. Available potassium showed a linear increase with biochar application from 0 to 40 g kg^{-1}, with the highest improvement observed at 40 g kg^{-1}. Notably, even 5–10 g kg^{-1} CPH biochar was sufficient to maintain the available K required for supporting plant growth, suggesting this as the recommended dose.

Since potassium in soil exists in dynamic equilibrium among its fractions, an increase or decrease in one fraction is balanced by transformation from other pools. CPH biochar, being a rich source of multiple K fractions, can thus act as a reservoir to replenish available K when soil potassium is depleted due to crop uptake or losses. The available K (sum of water-extractable and exchangeable K) increased by 23.7%, 40%, 79.9%, and 103.5% with 5, 10, 20, and 40 g kg^{-1}biochar, respectively. In contrast, the increase in non-exchangeable K was relatively small, recorded at 2.2%, 2.9%, 3.0%, and 7.6% under the same treatments. The formation of exchangeable and non-exchangeable K is primarily influenced by the binding interactions between potassium ions and soil surfaces (Li *et al.,* 2024). To maintain equilibrium, different forms of K can interconvert and contribute to replenishing depleted fractions. Therefore, biochar application not only expands the available potassium pool but also strengthens the long-term potassium supply accessible to plant roots (Mulet*et al*., 2023).

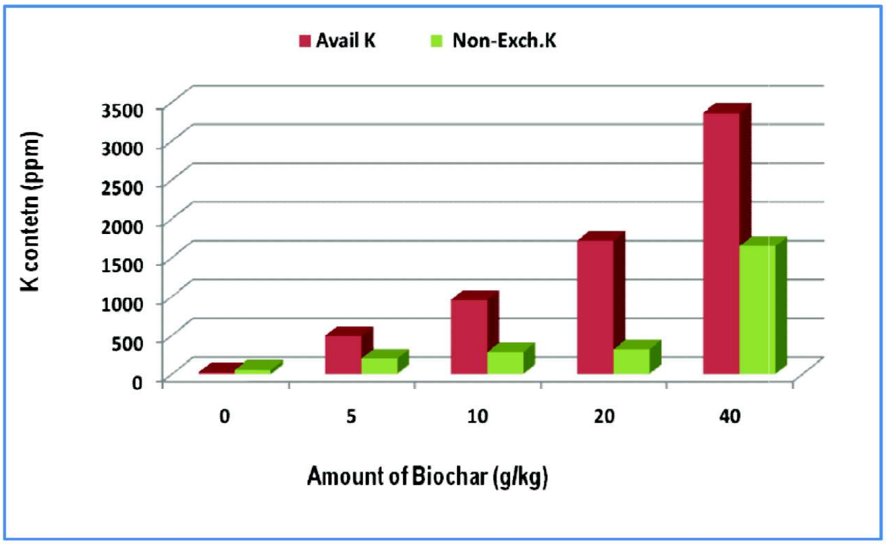

Fig 2. Effect of CPH biochar on available and non- exchangeable K in the soil

Lattice K and total K

Lattice potassium is the least accessible form of K to plants compared with other fractions; however, it plays a critical role in determining the soil's long-term potassium-supplying capacity and often constitutes a large proportion of total K. In this study, more than 90% of the total potassium was found in the lattice fraction. Although the lattice K content increased numerically with higher levels of CPH biochar addition, its proportion relative to total potassium decreased in biochar-amended soils. As a reserve pool, lattice K can replenish other fractions when depletion occurs. The application of CPH biochar from 5 to 40 g kg^{-1} increased the lattice K content, with the highest value observed at 40 g kg^{-1}. Similarly, total K also increased with biochar addition due to the rise in all fractions, including lattice K, with the maximum at 40 g kg^{-1}. Unlike other fractions, the ratio of lattice K to total K decreased with increasing biochar application, being the highest in the control and the lowest at 40 g kg^{-1}. This suggests that CPH biochar addition favored the retention of available forms of K over non-exchangeable and fixed forms. The proportion of lattice K and that of other K fractions related to total K was found to be negatively correlated.

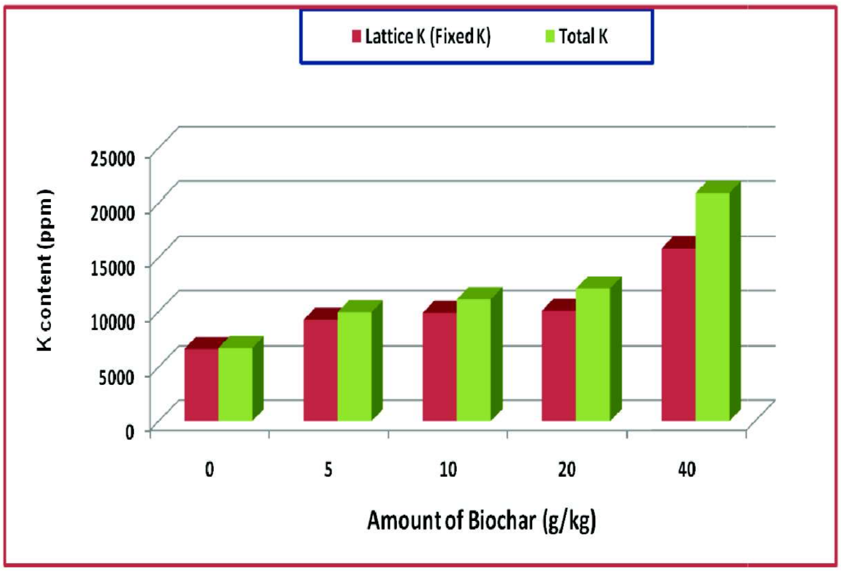

Fig 3. Effect of CPH biochar on lattice K and total K in the soil

The lattice K fraction was highest at the maximum level of CPH biochar application, primarily due to the contribution of insoluble potassium from the biochar itself. As cocoa pod husks are inherently rich in potassium, the biochar derived from them also contains substantial amounts of total K. The total potassium content in soil, however, is largely influenced by the clay content and the type of potassium-bearing minerals present (Mushtaqand Raj, 2008).

Per cent of K fractions to the Total K

The percentage contribution of different potassium fractions to total K under varying levels of CPH biochar addition is presented in Fig. 4. In the control treatment, the order of fractions was lattice K > non-exchangeable K > exchangeable K > water-extractable K. With 5 g kg^{-1} and 10 g kg^{-1} CPH biochar, the distribution changed to lattice K > exchangeable K > non-exchangeable K > water-extractable K. In contrast, soils amended with 20 g kg^{-1} CPH biochar showed the trend lattice K > exchangeable K > water-extractable K > non-exchangeable K, while the highest biochar application (40 g kg^{-1}) resulted in the order lattice K > exchangeable K > non-exchangeable K = water-extractable K.

The relative increase in all the fractions except lattice K indicates that CPH biochar addition is beneficial for plant growth, as water-extractable, exchangeable, and non-exchangeable fractions contribute directly to the pool of plant-available K. Typically, the distribution of potassium fractions follows the order water-soluble K < exchangeable K < non-exchangeable K < lattice K < total K, largely due to the depletion of available forms through crop uptake (Srinivas *et al*., 2019).The potassium content in CPH biochar is not only high but also highly available, with as much as 60% occurring in a water-extractable form. This characteristic makes it a valuable source of immediately available potassium for plants (Gopal *et al*., 2024). Other researchers have shown that incorporating bentonite into the substrate during biochar production can further improve potassium availability, as demonstrated with aquatic *Canna indica* plants (Chen *et al*., 2023).

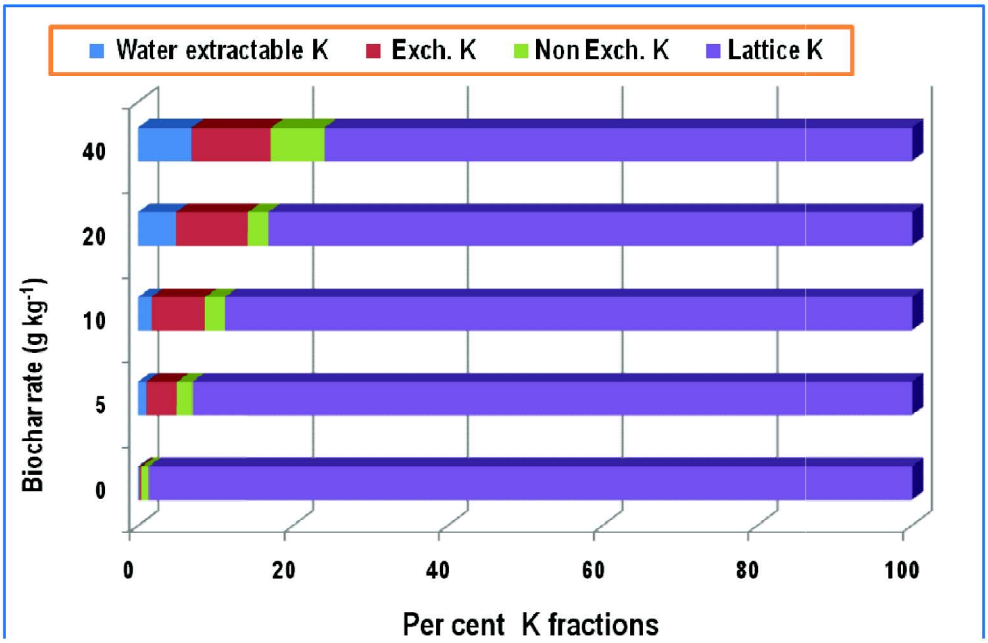

Fig 4. Per cent K fractions to the total K

Conclusion

Findings from this study clearly indicated that the CPH biocharenhancedthe various potassium fractions in soil. Among the different K fractions, the water-extractable and exchangeable fractions were important as they were the immediately available fractions in the soil solution. The improvement in the available fractions of K with the addition of CPH biochar made it as a good source of K to plants and can be exploited commercially. The K supplying capacity of cocoa pod huskbiocharwas significantly higher compared to many other biochars of different feedstocks like coconut husks, maize straw, rice straw,etc. (Gopal *et al*., 2020; Liqun*et al*., 2023; Zhang*et al*., 2025. The non-exchangeable and lattice K in soil also improved by cocoa pod huskbiochar addition and this might help in maintaining the equilibrium between various forms of K in soil solution.

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