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Neem cake as a component of integrated nitrogen management: effects on yield, soil carbon sequestration and environmental impact in coffee (*Coffea arabica L.*) grown under agroforestry system

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Abstract : A field experiment was conducted over the five years (2017-2022) at Central Coffee Research Institute, Coffee Research Station (CRS), Chikkamagaluru district, Karnataka, India. The experiment was laid out in Factorial randomised block design (RCBD) with the two forms of neem cake manures (Oiled & De-oiled) along with the four levels of neem cake (600 to 1500 kg ha^{-1}) and control. Among the varied levels of neem cake, application of neem cake @ 1200 kg ha^{-1}+ 60 kg RDN + 100% RD – P_2O_5 & K_2O (F_4) registered significantly higher clean coffee yield (675, 707, 741, 802, 828 and 750 kg ha^{-1}) which was statistically on par with F_5 -1500 kg ha^{-1}+ 45 kg RDN + 100% RD - P_2O_5 & K_2O (570, 604, 802, 761, 836 and 715 kg ha^{-1}, respectively) and F_3 - 900 kg ha^{-1}+ 75 kg RDN + 100% RD - P_2O_5 & K_2O (644, 668, 695,731,799 and 718 kg ha^{-1}, respectively). The lower clean coffee yields (525, 546, 552, 716, 744, 696 kg ha^{-1}, respectively) were observed in the control (100% RDF) during all the years of study, with a pooled mean. The same treatment combination resulted in a higher level of soil organic carbon build-up (0.3 to 0.38%) and an increase in soil organic carbon pools (8 to 10 Mg ha^{-1}) compared to its initial level. Additionally, due to the reduction in the use of nitrogenous fertilisers, these treatments help reduce GHG emissions without compromising yield levels. Therefore, the present study's results suggest that neem cake-based integrated nitrogen management in coffee is a sustainable nutrient management option under a changing climatic scenario.

Keywords: *Arabica coffee, Coffee yield, Neem cake, Organic carbon, and Soil microbial count*

Introduction

Coffee is one of the important plantation crops of high economic significance, experienced significant production growth over the past decade as a result of increased world coffee consumption (Torga & Spers, 2020). It is the most consumed and popular beverage in the world, after water, with 173.1 million bags of 60 kg each being consumed worldwide during 2022–2023, and the trend continues to rise. On average, 500 billion cups of coffee are consumed worldwide every year, resulting in an average of $20 billion in annual exports (Anonymous, 2024a).This sector has a retail market value of US $83 billion and an annual turnover of US $83 billion globally, providing jobs for 125 million people (Voora et *al.*, 2019).

Shade-grown / agroforestry system coffee plantations are one of India's best-kept secrets. These

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coffee farms are located in tropical regions, where the sun shines brightly, warming the coffee mountains. Today, in the country, coffee is grown in about 4.84 lakh ha area with a production of about 3.52 lakh metric ton per annum and is predominantly cultivated by small growers who account for more than 99 per cent of the total holdings. India is the 7th largest producer of coffee in the world, with a share of about 3.40 per cent in the global Coffee Production. Further, India is the 6th largest exporter of coffee in the world, with a share of about 4.80 per cent of global coffee exports (Anonymous, 2024b). Due to the interplay of various biotic partners inside the coffee forest, the biomass production at any given time is relatively high. It is an established fact that organic wastes are building up rapidly in every unit area of a coffee farm because of the diversity of trees, herbs and shrubs. Coffee agroforestry systems (AFS) significantly enhance soil carbon sequestration and mitigate greenhouse gases. Diverse shade species and effective management practices improve soil organic carbon (SOC) through enhanced nutrient cycling, organic matter input, and slower decomposition. SOC, the largest carbon pool in these systems, highlights the role of coffee AFS in long-term carbon storage and sustainable greenhouse gas management. However, coffee farmers are not in a position to harvest the locked-up energy in these substrates. Coffee farmers need to be aware that the limitation to the increased productivity of coffee is not the soil nutrients, but the rate of recycling of biomass within the confines of the coffee mountain(Anand & Geeta, 2005).

The standard and adoptable strategy for increasing crop yields and sustaining them at a high level must include an integrated approach to the management of soil nutrients, along with other complementary measures(Peter *et al.,* 2000). "Arista" is the Sanskrit name of neem (*Azadirachta indica), meaning "perfect, complete and impermeable, Neem* is documented as a natural product which has much to offer in solving global, agricultural and health problems *(Jaganathan et al., 2016*). Field application of neem and other concentrated cakes in different forms acts as a precursor for the stimulation of beneficial microflora, thereby releasing the locked-up energy in the accumulated biomass, converting it into energy-rich compounds. The dense mulch and organic matter on the floor bed of the plantation, together with neem, increases heterotrophic microbial activity and organic matter decomposition, thus regulating nitrogen release from nitrogenous fertilisers. Neem cake organic manure has been traditionally used in India as manure for soil application for more than 5 decades, especially in southern states like Karnataka, Tamil Nadu and Kerala. The coffee growers are in an advantageous position with regard to their availability in large quantities at a reasonable cost, and are available in areas surrounding plantation districts. It is one of the best-suited economically viable components in INM. These organic cakes and their derivatives act as prophylactic agents in the management of pest and disease incidence as well. Keeping the above background in mind, a field trial was conducted to evaluate the effect of neem cake-based integrated nitrogen management on yield, soil carbon dynamics and environmental footprint in coffee (*Coffea arabica L.*) grown under an agroforestry system.

Materials and Methods

A field experiment was conducted over the period of five years (2017-2022) at Coffee Research Station (CRS), Chikkamagaluru District of Karnataka, India. The CRS farm is situated in the southern hill zone of Karnataka at 13°34' North Latitude and 75° 48' East Longitudes with an elevation of 757 metres above MSL. Average annual rainfall during the experimental period was 2500 mm, ranging from 2157 mm in 2017 to 3860 mm in 2018. The mean monthly minimum and maximum temperatures over the experimental period were 18.51 °C and 28.25°C, respectively. The mean monthly minimum and maximum RH over the period were 66 per cent and 94 per cent (Table 1).

Table 1: Geographical coordinates and total rainfall (mm) and number of rainy days received during the period of experimentation from 2017 to 2022

Year	Annual rainfall (mm)	No of rainy days (no)	Geographical co-ordinates	Altitude
2017	2157	113	13°34°north latitude and 75° 48° east longitudes	757 meters above mean sea level
2018	3860	127		
2019	3083	113		
2020	2755	113		
2021	2641	113		
2022	3405	125		

The experiment was laid out in Factorial Randomised Block Design (RCBD) with the two forms of neem cake (Oiled & De-oiled) along with the four levels of neem cake (600, 900, 1200, and 1500 kg ha^{-1}) and control. The treatments details are as per below:

Treatment details		
M1	-	Oiled neem cake
M2	-	Deoiled neem cake
S1	-	Control (100 % RDF)
S2	-	600 kg NC/ha (200 g/plant) + 90 kg RDN + 100% RD - P& K
S3	-	900 kg NC/ha (300 g/plant) + 75 kg RDN + 100% RD - P& K
S4	-	1200 kg NC/ha (400 g/plant) + 60 kg RDN + 100% RD- P& K
S5	-	kg NC/ha (500 g/plant) + 45 kg RDN + 100% RD -P& K

The coffee cultivar used in the experiment was Sln-6, aged about 15 years. In this study, the methodology adopted to measure greenhouse gas (GHG) emissions involved two key components: soil organic carbon (SOC) stock calculation and the reduction of GHG emissions due to a decrease in nitrogenous fertiliser use. The SOC stock was calculated using the formula: Carbon (Mg ha^{-1}) =Soil organic carbon (%) ×Soil bulk density (Mg m^{-3}) × Sampling depth (cm). To estimate carbon sequestration, the quantum of carbon was converted into the quantum of carbon dioxide (CO_2) using the following equation: Quantum of Co_2 = Quantum of carbon×44/12 (Ajaykumar, 2003), where the atomic weight of carbon (C) is 12 and the atomic weight of oxygen (O) is 16. The weight of CO_2 is derived from the sum of carbon (C) and two oxygen atoms (O), resulting in a molecular weight of 44 (C + 2O). The ratio of CO_2 to C is therefore 44/12= 3.66. To determine the weight of CO_2 sequestered in the soil, the increase in soil organic carbon was multiplied by 3.66. The reduction in GHG emissions due to the reduction in urea fertiliser use was calculated using the emission factor provided by Brentrup *et al.* (2018). This method allowed for the estimation of GHG equivalents based on the reduction in nitrogenous fertiliser application, linking soil carbon sequestration and fertiliser use reduction to GHG mitigation.

Results and Discussion

Initial nutrient status

The initial soil samples were analysed for pH, Organic carbon (OC), Phosphorus, and Potassium content according to the standard procedure. The soil of the experimental site was sandy loam (17.5% clay, 23.9% silt and 58.6% sand), initial soil organic carbon was 2.60 per cent, and the bulk density of the experimental location was 1.2 g cm^{-3}. The soil was acidic in reaction with high organic carbon, available phosphorus and high available potassium. Soil available N, P and K contents were analysed using standard analytical procedures (Jackson, 1973). The properties showed that there is no considerable variation among the physico-chemical properties of the soil at the time of imposition of the treatment (Table 2).

Table 2: Initial nutrient status of the experiment block

Soil parameter	Values
pH (1:2.5)	5.80
Soil Organic carbon (g kg^{-1})	2.60
Bulk density (g cm^{-3})	1.20
Particle size distribution	
Sand (%)	58.6
Silt (%)	23.4
Clay (%)	17.5
Textural class	Sandy loam
Soil microbial count	
Fungi population Bacteria population	40X 10^{-3} 196 X 10^{-5}
Available P_2O_5 (kg ha^{-1})	77
Available K_2O (kg ha^{-1})	382

This comparative study, conducted in the same field over a five-year period, supports the general hypothesis and is consistent with previous research (e.g., Surendran *et al.,* 2016a, b). As noted by Anand and Geeta (2005), broadcasting neem seeds onto the field helps stabilise the carbon-to-nitrogen ratio, boosting microbial activity, enhancing organic waste utilisation and stimulating soil microflora. The dense mulch and organic matter on the plantation floor, combined with neem, promote heterotrophic microbial activity and accelerate the decomposition of organic matter. Throughout the study, neem cake was applied annually according to the specific treatment plan.

Clean coffee yield

The forms of neem cake had a non-significant influence on the clean coffee yield during all the years of study and the pooled mean, respectively. Numerically higher clean coffee yield was recorded in application of de-oiled form of neem cake (S_2) (572, 600, 700, 772, 833 and 695 kg ha^{-1}, respectively) as compared to oiled neem cake (S_1) (624, 652, 689, 748, 756 and 694 kg ha^{-1}, respectively) during all the years of study (except 2017 and 2018) and pooled mean, respectively. However, different levels of neem cake exerted a significant influence on clean coffee yield. Among the varied levels of neem cake, application of neem cake @ 1200 kg ha^{-1} (400 gm $plant^{-1}$) + 60 kg RDN + 100% RD- P_2O_5 & K_2O (F_4) registered significantly higher clean coffee yield (675, 707, 741, 802, 828 and 750 kg ha^{-1}) which was statistically on par with **F_5** -1500 kg ha^{-1}neem cake (500 gm $plant^{-1}$) + 45 kg RDN + 100% RD - P_2O_5 & K_2O (570, 604, 802, 761, 836 and 715 kg ha^{-1}, respectively) and **F_3 -** 900 kg ha^{-1} neem cake (300 gm $plant^{-1}$) + 75 kg RDN + 100% RD - P_2O_5 & K_2O (644, 668, 695, 731, 799 and 718 kg ha^{-1}, respectively**)** during all the years of study and pooled mean, respectively. The next best treatment was **F_2 :** 600 kg neem cake ha^{-1}(200 gm $plant^{-1}$) + 90 kg RDN + 100% RD - P_2O_5 & K_2O (577, 606, 683, 738, 764 and 674 kg ha^{-1}, respectively). The lower clean coffee yields (525, 546, 552, 716, 744, 696 kg ha^{-1}, respectively) were recorded in the control (100% RDF) during all the years of study, with a pooled mean. The interaction effect between different forms of neem cake and varying levels of neem application on clean coffee yield was not significant during all years of study, as indicated by the pooled mean (Table 3).

During the initial three years, the lower increase in the yield may be due to the effect of the soil conversion period, and also might be due to the non-availability and supply of the secondary and trace elements as demanded by the crop during the differential growth and development. Similar results were recorded by Anand and Geeta (2005). Under different levels of neem cake treatments higher clean coffee yield recorded as compared to control (100 % RDF) might be due highly positive impacts of neem cake by causing the positive changes in terms of both soil physical, chemical and biological properties, the increase soil organic carbon (g kg^{-1}) and soil microbial load (µg g^{-1}). Similar kinds of effects were noticed by Anand & Geeta (2005). Similarly, as reported by Agyarko *et al.* (2006) the increase in soil pH has indicated that there was a positive impact on the biochemical process by inhibiting the process of nitrification and enhances N use efficiency by the application of neem cake manure and in addition, it promotes the enzyme activity and the total microbial count in the root rhizosphere region that supported to produce higher level of vegetative and bearing wood.

Table 3: Clean coffee yield (CC Yield) as influenced by forms and varied levels of neem cake over the five years and pooled mean

Treatments	CC Yield (kg ha^{-1})					
	2017-18	2018-19	2019-20	2020-21	2021-22	Pooled
Forms of Neem cake						
S1: Oiled neem cake	624	652	689	748	756	694
S2: De-oiled neem cake	572	600	700	772	833	695
S.Em±	**27.71**	**28.86**	**33.77**	**9.35**	**26.10**	**18.03**
CD @ 5 %	**NS**	**NS**	**NS**	**26.73**	**75.49**	**NS**
Different Levels of Neem cake						
F1: Absolute control (100 % RDF *i.e.*, 120:90:120 kg N, P_2O_5 & K_2O NPK ha^{-1})	525	546	552b	716c	744b	616b
F2: 600 kg neem cake ha^{-1} (200 gm $plant^{-1}$) + 90 kg RD N + 100% RD - P_2O_5 & K_2O	577	606	683ab	738b	764b	674ab
F3: 900 kg neem cake ha^{-1} (300 gm $plant^{-1}$) + 75 kg RD N+100% RD - P_2O_5 & K_2O	644	668	695ab	731b	799a	718a
F4: 1200 kg neem cake ha^{-1} (400 gm $plant^{-1}$) + 60 kg RD N + 100 %RD - P_2O_5 & K_2O	675	707	741a	802a	828a	750a
F5: 1500 kg neem cake ha^{-1} (500 gm $plant^{-1}$) + 45 kg RD N + 100 % RD - P_2O_5 & K_2O	570	604	802a	761a	836a	715a
S.Em±	**43.82**	**45.63**	**53.40**	**13.94**	**13.33**	**28.51**
CD @ 5 %	**NS**	**NS**	**158.6**	**41.08**	**38.57**	**84.73**
Interaction effect						
S1F1	559	587	558	741	711	631
S1F2	606	629	694	732	721	677
S1F3	671	707	654	789	758	716
S1F4	690	723	726	757	784	736
S1F5	597	614	813	722	805	710
S2F1	492	505	546	692	777	602
S2F2	548	583	671	745	804	671
S2F3	616	629	737	774	840	719
S2F4	660	691	757	847	872	765
S2F5	544	593	791	804	867	720
S.Em±	**61.98**	**64.53**	**75.52**	**54.90**	**44.5**	**40.33**
CD @ 5 %	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

Change in Soil organic carbon (%) and reduction of GHG emission

Perusal of the data presented in Fig. 1 revealed that the change in soil organic carbon and greenhouse gas reduction was influenced markedly by varying levels of neem cake during all the years of study, as well as the pooled mean. Control (100% RDF) (F_1) maintained a lower increase in soil organic carbon (0.12%) over the initial level and showed no greenhouse reduction throughout the study period. Whereas, in neem cake levels, *viz*., F_5 (1500 kg ha^{-1} neem cake (500 g plant^{-1}) + 45 kg RDN + 100% RD - P & K) and F_4 (1200 kg ha^{-1} neem cake (400 g plant^{-1}) + 60 kg RDN + 100% RD – P & K) the higher raise in soil organic carbon (0.36 and 0.36 %) over initial level and more GHG reduction (840 and 672 kg CO_2eq) as compared to control (100 % RDF) (F_1).

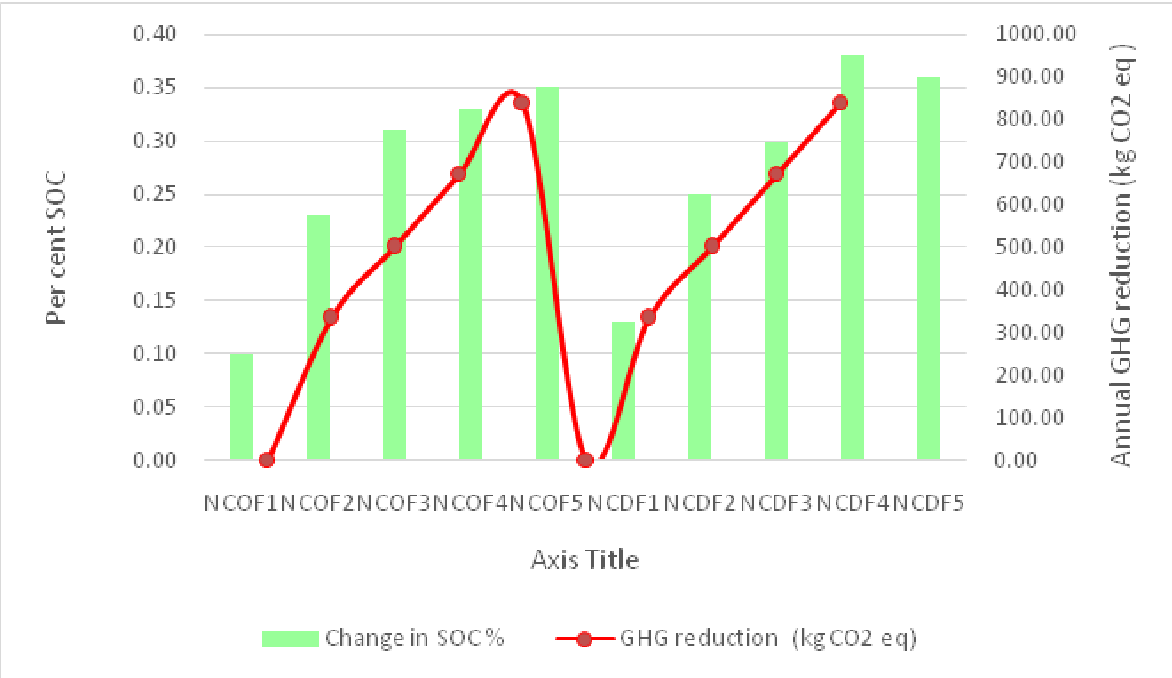

Fig. 1: Soil organic carbon and greenhouse gas reduction as influenced by neem cake-based Integrated Nutrient Management Practices

This may be due to congenial and optimal soil conditions, resulting from the continuous application of neem manure, which led to higher total soil bacterial and fungal loads, being *582* x *10*^{4} *& 155* x *10*^{3} and *551* x *10*^{4}*& 92.5*x10^{3}in de-oiled and oiled neem cake blocks, respectively. As the microbial load increased, the decomposition process accelerated, resulting in an increase in soil organic carbon from 17.69 g kg^{-1} to 19.97 g kg^{-1} under different levels of neem cake applied treatments. The soil organic carbon (0.24 and 0.30%) and greenhouse reduction (336 and 504 kg CO_2eq) in F_3 (900 kg NC ha^{-1} (300 g plant^{-1}) + 75 kg RDN + 100% RD - P& K) and F_2 (600 kg NC ha^{-1} (200 g plant^{-1}) + 90 kg RDN + 100% RD - P& K) dropped marginally relative to F_4 and F_5 indicating that the adoption of integrated nutrient management with the neem cake had positive impact on soil and environment health. Present study results are in the similar line with Yadav *et al.* (2019) who reported that the maximum per cent organic carbon in soil was recorded 0.76 per cent in treatment T_8 (@100% NPK + 100% Neem cake) which was significantly higher than any other treatment combination and the minimum % Organic carbon in soil was recorded 0.48 % in treatment T_0 (control). Similar findings were recorded by Kumar *et al.* (2008).

Soil carbon gain and CO_2 removal

Soil organic carbon gain and CO_2 removal /Seqat soil are measured during the study period as influenced by different neem cake levels are depicted in Figure 2.

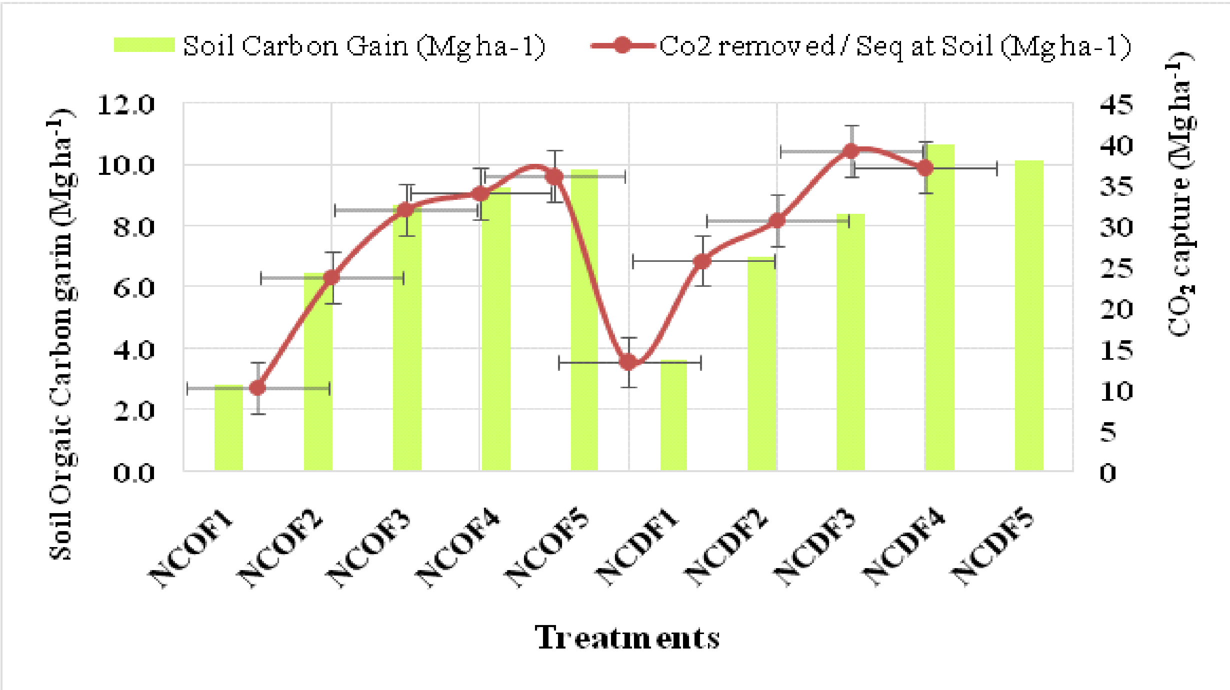

Fig. 2: Soil carbon gain and CO_2capture at the soil as influenced by neem cake-based Integrated Nutrient Management Practices

Soil carbon gain and CO_2 removal in neem cake treatments were higher than the control (100% RDF) treatment (3.2 and 12 Mg ha^{-1}) throughout the entire study period. Among different levels of neem cake, F_5 (1500 kg ha^{-1} neem cake, equivalent to 500 g per plant, plus 45 kg RDN and 100% RD - P & K) and F_4 (1200 kg ha^{-1} neem cake, 400 g per plant, plus 60 kg RDN and 100% RD – P & K) showed significantly higher soil carbon gain and CO_2 removal values (10 and 37 Mg ha^{-1}) compared to F_3 (900 kg ha^{-1} neem cake, 300 g per plant, plus 75 kg RDN and 100% RD - P & K) (8.6 and 31 Mg ha^{-1}) and F_2 (600 kg ha^{-1} neem cake, 200 g per plant, plus 90 kg RDN and 100% RD - P & K) (6.8 and 25 Mg ha^{-1}). This may be attributed to the reduction of nitrogen dose from chemical sources and the application of a balanced amount of nitrogen through organic sources such as oiled and de-oiled neem cake doses, which could lead to increased microbial activity, among other effects. Similarly, Yadav et al. (2019) reported that neem cake fertiliser in treatment T_8 (20 kg N, 40 kg P, 40 kg K, and neem cake 5 q ha^{-1}) significantly influenced soil physical and chemical parameters such as bulk density, particle density, pore space percentage, EC, pH, organic carbon, and available NPK compared to other treatment combinations.

Conclusion

Neem cake and its beneficial role on coffee farms will undoubtedly help address the challenging questions of tomorrow. From this study, it was concluded that applying neem cake at 1200 kg NC ha^{-1} (400 g plant^{-1}) along with 60 kg RDN and 100% RD - P & K (F_4) was optimal for improving soil parameters such as Organic Carbon (%) and Microbial count, as well as increasing coffee yield by 15-18%. Additionally, adopting neem cake-based integrated nutrient management in coffee cultivation can enhance soil organic carbon build-up and significantly reduce greenhouse gas emissions. Therefore, neem cake not only promotes soil health and microbial activity but also plays a vital role in carbon sequestration and the mitigation of greenhouse gases, supporting sustainable agriculture.

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