**Journal of Animal & Plant Sciences, 34(5): 2024, Page: 1275-1289**
**ISSN (print): 1018-7081; ISSN (online): 2309-8694**
https://doi.org/10.36899/JAPS.2024.5.0810

# INFLUENCE OF MINERAL NUTRITION ON THE SOIL HEALTH AND PRODUCTIVITY OF COCONUT PALMS (*Cocos nucifera* L.) IN TROPICAL LAND USE SYSTEMS

J. Mathew[1, *], A. A. Haris[1], S. Indhuja[1], K. M. Nair[2], V. Krishnakumar[1], R. Bhat[3] and S. Shil[3]

[1]ICAR-Central Plantation Crops Research Institute, Regional Station, Kayamkulam, Kerala, India
[2]ICAR-National Bureau of Soil Survey and Land Use Planning, Regional Centre, Bangalore, Karnataka, India
[3]ICAR-Central Plantation Crops Research Institute, Kasaragod, Kerala, India
*Corresponding Author's Email: jeenu15@gmail.com
ORCID ID: https://orcid.org/0000-0001-7759-7384

## ABSTRACT

Perennial plantation crops, such as coconut trees require the systematic addition of nutrients for sustained growth and productivity. This study aimed to understand plant and soil nutrient dynamics, root health and soil biological properties upon addition of specific nutrients in tropical land use systems. Field experiments in randomised block design were conducted in Agro-Ecological Unit-3 (AEU-3) and Agro-Ecological Unit-9 (AEU-9) from 2014 to 2020. Treatments were $T_1$ (site-specific nutrient management practices (SSNM), $T_2$ (SSNM without sodium chloride); $T_3$ (SSNM without gypsum); $T_4$ (SSNM along with the 50 g microbial formulation Kera Probio); $T_5$ (Farming practice without any amendments or nutrients). Root health parameters, cumulative nut yield and nutrient dynamics in soil and leaf samples were estimated at the beginning and the end of the study. Systematic provision of all the essential nutrients resulted in significant increase content of N (1.39%), P (0.164%), K (1.71%), Ca (0.406%) and Mg (0.175%) in index leaves of coconut trees in sandy soils. Foliar nutrient levels of coconut trees grown in laterite soils were 1.21% N, 0.142% P, 1.27% K, 0.504% Ca and 0.146% Mg. In AEU-3, treatment that received all amendments and nutrients showed highest organic carbon content at the three depths as 6.79 g $kg^{-1}$soil, 5.39 g $kg^{-1}$ soil and 3.82 g $kg^{-1,}$ soil, respectively. In AEU-3, 61% increase in yield was observed, while in AEU-9,40% increase was recorded. Application of gypsum resulted in downward displacement of K and Mg indicating that gypsum is required for the amelioration of sub soil acidity in sandy soils. However, the displacement effect was less pronounced in laterite soils and beneficial effect of gypsum was evident with the enhancement of exchangeable Ca. Hence sandy soils require application of inputs as per T3 (T1 without gypsum), with external organic inputs and palm residues whereas in laterite soils application of treatments as per T1 is required with in situ palm residue recycling.

**Key words:** coconut, leaf nutrients, sandy soil, laterite soil, root health, dehydrogenase.



Published first online September 11, 2024 Published final October 22, 2024

## INTRODUCTION

The coconut tree (*Cocos nucifera* L.) is a perennial plantation crop adaptable to various soil types, including laterite, lateritic, coastal sands, and alluvial, red, and sandy soils. It is distributed globally in 93 countries. It is also called 'Kalpa Vriksha', a term derived from the ancient Indian language Sanskrit, meaning 'Heaven's Tree'. The palm flourishes well in areas with well distributed rainfall of greater than 1200mm. In India, the coconut tree is largely grown in Kerala (0.77million ha), followed by Karnataka (0.514 million ha) and Tamil Nadu (0.461 million ha) (Coconut Development Board, 2020). The ideal soils for cultivating coconut are red loams with good drainage, a minimum depth of one metre, adequate levels of major nutrients such as N, P and K, secondary nutrients such as Ca, Mg and S and micronutrients such as B and Zn, as well as good water-holding capacity (Fremond,1964).

Coconut palms have a lifespan of 60 – 70 years and start flowering by the fifth year of planting. Once the palms start flowering, the vegetative and reproductive phases occur simultaneously. During its productive period, the palm removes large amounts of nutrients from the soil for growth and yield, warranting the systematic application of nutrients to the soil. This indicates reduced palm productivity due to nutrient exhaustion unless soil nutrient constraints are addressed. The total nutrient uptake of apparently healthy coconut palms of 25 years age, grown in entisols was 889 g $palm^{-1}$ of N, 109 g $palm^{-1}$ P, 1075 g $palm^{-1}$ K, 389.7g $palm^{-1}$Ca, 71.6 g $palm^{-1}$ Mg and 321.6 mg $palm^{-1}$B (Mathew *et al.* 2021). Hence, considering their total nutrient uptake and the versatile role of coconut palms in daily life, systematic nutrient

management practices should be implemented to improve and sustained productivity.

About 40% of the cropped area in Kerala is occupied by coconut palms in small homesteads, predominantly in tropical sandy and laterite soils. Such soils have inherent fertility constraints such as low organic matter, poor exchangeable base status, acidic soil reaction, and low beneficial microbial activity. Strong acidic soil reactions, low organic carbon levels, high available P levels, and deficient K, Ca, Mg, Cu, and Zn levels in coconut-growing soils were reported by Nair *et al*. (2018). Besides coconut kernel, most crop residues, such as dry leaf fronds, dry spathes, coconut husks, and coconut shells, are removed from the plantation for thatching, burning, coir retting and other purposes (Menon and Pandala, 1958). This poor organic matter recycling is one of the causes of declining soil health and low yields in coconut-based cropping systems. Therefore, discovering management options to overcome these constraints and improve coconut palm productivity in the long run, is imperative. Nutrient balance must be maintained by replenishing nutrients exported through harvested produce and above-ground parts through external input (Khan *et al*.2018).

Soil and foliar nutrient levels have a direct relationship with palm productivity. Assessing leaf nutrient status is a real-time indicator of palm health status. Nutrient absorption and translocation from soil to plants and, ultimately, to the photosynthates is a complex phenomenon. Hence, assessing the nutrient status in coconut palm leaf and soil will indicate the effect of management practices on palm productivity.

Based on these considerations, it was hypothesised that site specific management of soil constraints by adding nutrients and amendments to perennial coconut palms grown in different land use systems could influence soil and plant nutrient dynamics and soil biological properties. The hypothesis was tested by conducting a comprehensive, long-term study (2014-2020) to investigate the effects of specific nutrients, amendments and crop residue incorporation on foliar nutrient levels, root health parameters, soil biochemical properties, and palms performance in tropical sandy and laterite soils following the addition of nine essential nutrient elements (N, P, K, Ca, Mg, S, Cu, Zn and B and soil amendments such as lime, dolomite and gypsum.

## MATERIALS AND METHODS

***Study sites:*** Investigations into the improvement of soil quality and the health of coconut palms were conducted from 2014 to 2020 in the palm groves in Agro Ecological Unit -3 (AEU-3), the Onattukara Sandy Soil (Usti psamment subgroup), located at Chettikulangara, Alappuzha district (9.2273° N, 76.5159° E), Kerala, India, and Agro Ecological Unit -9 (AEU-9), the south-central laterite soils (Typic Plinth Ustult), located at Kalluvathukkal, Kollam district (8.8279° N, 76.7481° E), Kerala, India.

***Experimental layout:*** The experiment was carried out in a coconut garden using a variety of West Coast Tall, aged 25 – 30 years, in a randomised block design with five treatments; each replicated four times. There were six palms per treatment per replication, with 120 experimental palms at each site. The treatments were as follows:$T_1$ site-specific nutrient management practices (SSNM), including the per-palm annual application of 500 g N: 0 g $P_2O_5$: 1200 g K, 1 kg magnesium sulphate, and 2 kg sodium chloride), amendments such as 1 kg each of lime and dolomite palm$^{-1}$, 2 kg gypsum palm$^{-1}$ and micronutrients such as Zn, B, and Cu; $T_2$ (SSNM without sodium chloride); $T_3$ (SSNM without gypsum); $T_4$ (SSNM along with the 50 g of the microbial formulation Kera Probio 50 g palm$^{-1}$); $T_5$ (Farming practice without any amendments or nutrients). The primary nutrients N and K were supplied through urea (46% N) and muriate of potash (60% $K_2O$). Based on the soil test data, phosphorus was not added due to its high content.

Moreover, micronutrients such as Zn, B, and Cu were supplied as 100 g zinc sulphate per palm$^{-}$, 150 g borax palm$^{-1}$ and 50 g copper sulphate palm$^{-1}$ for all the treatments other than $T_5$ In our study, lime and dolomite were used as amendments to improve surface acidity, while gypsum was used to improve subsoil acidity. The treatments were applied in a circular pattern around the base of the palm, 1.5 m away from the trunk. The palms were grown under rainfed conditions, and the treatments were administered twice during the southwest monsoon (May – June) and the northeast monsoon (September – October). Palm residues, including dried leaves and bunch wastes, were added to the palm basin for gradual decomposition, and the treatments were applied without opening the basin.

***Collection, preparation, and analysis of soil and leaf samples***

***Soil sampling:*** The fertility status of AEU-3 and AEU-9 was assessed periodically before and after the end of the study. Soil samples were collected from three depths at 0 – 20 cm, 21 – 40 cm, and 41 – 60 cm from the diagonally opposite points at one metre from the palm trunk. They were combined to obtain a representative sample from each palm basin at each depth. Soil samples were analysed for pH (1:2.5 soil solution), electrical conductivity, organic carbon, available P, K, Ca, Mg, S, Mn, Cu, Zn, and B. Soil biological (dehydrogenase) activity was assessed using the previously described method of Casida *et al*. (1964). Soil samples were processed separately and stored at 4ºC for microbial analysis. The population counts of general microbial

groups, such as heterotrophic bacteria, filamentous fungi, and actinomycetes, as well as functional groups, such as fluorescent pseudomonads, phosphate solubilisers, and free-living nitrogen (N) fixing bacteria, were determined through serial dilution and plating technique with appropriate soil dilutions and specific growth media (Pelcazar *et al*.1957).

***Leaf sampling:*** Index leaf samples for nutrient analysis were selected using the formula N/2 or N + 1/2, where 'N' is the total number of leaves in the crown, counting from the top (Menon and Pandalai, 1958). The leaflets were also collected from the youngest fully opened leaf to estimate immobile nutrients such as Ca, B, and Mn. Necessary permissions were obtained for the collection of samples. Three leaflets on either side were sampled from the middle of the leaf after removing the midrib (Fremond, 1964). The leaf samples were analysed for total nutrients such as N, P, K, Ca, Mg, Mn, Cu, Zn, and B before and after the study. All methods were carried out in accordance with relevant guidelines and regulations regarding safety precautions while preparing and analysing the samples.

***Root parameters:*** The root health parameters, such as the proportion of live roots and root dry weight in a fixed core volume, were recorded at the end of the study. Core samples were taken vertically at 1.5 metres from the palm trunk at 0 – 20 cm and 41 – 60 cm depths. Root samples were collected from the soil core and segregated into dead and live roots. The dry weights of the live roots and their proportions were recorded.

***Nut yield (nuts palm$^{-1}$ year$^{-1}$):*** The palm yield, an indicator of its productivity, was periodically recorded by harvesting once in 50 days, and the cumulative yield was determined annually.

***Statistical analysis:*** All the experimental data represented the average of four replications. The collected data from the experiments were statistically analysed using Gomez and Gomez, (1984) method for variance ($p < 0.05$) analysis. Means were compared by the Tukey's test. The analysis was performed using the Statistical Package for the Social Sciences Software version 16(IBM, 2016).

## RESULTS

The pre-experimental soil fertility status (Table S2) for AEU-3 indicated a strongly acidic soil reaction (pH 5.0-5.5) whereas the soil was extremely acidic (pH: 4.0-4.5) in AEU-9. Both sites were non- saline and having high available P. The contents of exchangeable K, Ca and B were at deficient levels. The initial foliar nutrient levels at both sites indicated sufficiency of all the nutrients except Mg in AEU-3, whereas deficient levels of K, Ca, Mg and B were observed in AEU-9. The microbial populations of general and functional groups in the soil profile (3 depths) from AEU-3 and AEU-9 indicated that AUE-3 harboured a smaller population of heterotrophic bacteria, filamentous fungi, actinomycetes and N-fixing bacteria in the topsoil compared with AEU-9 (Fig.S3). Fluorescent pseudomonads were found in 20cm and 40cm depth of AEU-3, whereas in AEU-9 they were restricted to the topsoil. Phosphate solubilizing bacteria were detected only at the depth of 41-60cm of AUE-3 with a mean population of $1.43\times10^3$ cfu/g dry weight of soil. However, the population reduction in subsequent lower soil depths was more pronounced in AEU-9 for fungi.

***Effect of treatments on available nutrients:*** The effect of treatments on soil nutrient availability was evident in AEU-3 (Table 1), particularly regarding soil reaction, organic carbon content, and available K, Ca, and Mg. Improved pH was observed at all depths for the treated plots compared with T5. Enhancement of soil organic carbon was evident in T1 compared to other treatments at all depths. Treatment without gypsum (T3) resulted in significantly higher K and Mg levels than other treatments. Except for T5, all treatments showed improvements in available K levels compared with the baseline. Treatment without sodium chloride (T2) resulted in the highest exchangeable Ca, followed by T3. Treatment effects were insignificant and inconsistent on the available micronutrients in the soil.

Treatment effects on the soil properties of AEU-9 (Table 2) indicated a two-unit rise in soil pH with application of amendments. Incorporation of the microbial formulation Kera Probio showed significantly increased organic carbon and available K content at all depths. Exchangeable Ca was highest at the 0 – 20 cm surface layer in T1 whereas T2 showed the highest content at the depth of 21 – 40 cm and 41 – 60 cm. Treatment without gypsum (T3) showed comparatively higher exchangeable Mg content at all depths. T5 recorded the lowest contents for all parameters.

***Effect of treatments on leaf nutrient status:*** Leaf nutrients such as P, K, Ca, Mg, and Zn was significantly influenced by the treatments in AEU-3, whereas the effects were significant for K, Ca, Mg, B, Mn, and Cu in AEU-9 (Table 3). A steady improvement in foliar nutrient levels except Mg was observed in both AEUs when nutrient concentrations were examined from 2015 to 2019 (Fig.1). A gradual decrease in the content of leaf P in sandy soils of AEU-3 was observed over the years, whereas the laterite soils of AEU-9 showed a gradual improvement in the content. The heatmap of Spearman's correlation as shown in figure 2 demonstrates the significant correlation of the foliar nutrients over the years. In AEU-3, treatment T3 showed significantly high positive correlation in 2018 and 2019 for leaf K. In AEU-9, the content of K reached sub optimal level in T2, the

treatment without NaCl and that in treatment T5. The improvement in T1 had a significant positive correlation as shown in the heatmap.

***Effect of treatments on soil dehydrogenase activity:*** Soil dehydrogenase activity showed a significant relationship with treatments in both AEUs (Table 1 and 2). The activity was comparatively higher in laterite soils. In sandy soils, T1 showed the highest activity compared with other treatments. However, in laterite soil, T4 with microbial formulation showed the highest activity at all depths. Surface soil samples showed higher activity for all treatments in AEU-9 except T4.

***Effect of treatments on soil microbial populations:*** Generally, bacteria were dominant at both sites, followed by actinomycetes and free-living N fixers. AEU-3 recorded a higher mean bacterial population (7.16 log cfu/g) than AEU-9 (6.84 log cfu/g) in the topsoil. AEU-9 recorded a significantly higher fungal population (5.25 log cfu/g) than AEU-3 (Table 4). Colony counts of actinomycetes were significantly higher at the 0-20cm depth of T4 (T1 with Kera Probio) in AEU-3, whereas T2 that lacked NaCl and showed higher counts of the same in AEU-9. The free-living N fixers that dominated the functional groups had a mean population of 6.20 and 6.18 log cfu/g in the topsoil of AEU-3 and AEU-9 with the highest counts of 6.47 log cfu/g in T5 (farmer practice) for AEU-3 and 6.44 log cfu/g in T1 for AEU-9. A smaller population of free-living N fixers was observed in the second depth of sandy soils in AEU-3 in a range of 5.32 to 5.86 log cfu/g whereas population counts of N fixers were on par in both the depths of laterite soil. A similar trend was observed for the bacterial population. Phosphate solubilizers were almost absent and hence had no treatment influence on either soil type.

***Effect of treatments on root health:*** The root health of the treated palms was assessed to identify the proportion of live roots and total root biomass quantified from a fixed soil volume (Tables 1 and 2). In AEU-3, T1 had the highest root biomass at 0 – 20 cm, whereas T3 had the highest biomass at the 21-40 cm and 41-60cm depths. The proportion of the live roots was significantly highest for T2 at 20 cm and 40 cm and for T1 at 60 cm. The magnitude of total root biomass increased with the depth in AEU-9 and treatment T4 with the microbial formulation showed the highest value at all depths. Similarly, the live roots proportion was highest at 21 – 40 cm depth, with T4 showing the highest value.

***Effect of treatments on coconut yield:*** When comparing the percentage increase in yield over the pre-treatment period in AEU-3, T3 exhibited a significantly higher increase (61%) during 2018 – 2019 without the use of gypsum (Fig.3). Pair-wise comparisons of annual yield between 2015-2016 and 2018 – 2019 indicated significant improvements in yield for treatments T3, T4, and T5, while there was an insignificant increase for T1 and T2. In AEU-9, the percentage increase in base yield ranged from 20% for T3 to 46% for T1. T1 produced the highest yield of 43 nuts by utilising all amendments and nutrients. The heatmap of Spearman's correlation presented in figure 2 indicated that treatment T3 (T1 without gypsum) was positively correlated with the yield of coconuts per tree.

**Table 1. Soil properties and root health parameters as influenced by treatments in AEU-3**

| Soil Properties | Depth (cm) | Treatments | | | | | CD |
|---|---|---|---|---|---|---|---|
| | | T1 | T2 | T3 | T4 | T5 | (0.05%) |
| pH | 0-20 | 6.26$^{a}$ | 6.25$^{a}$ | 6.26$^{a}$ | 5.60$^{b}$ | 5.52$^{b}$ | 0.56 |
| | 21-40 | 5.92$^{a}$ | 5.91$^{a}$ | 5.95$^{a}$ | 5.27 $^{b}$ | 5.19$^{b}$ | 0.602 |
| | 41-60 | 5.60$^{a}$ | 5.58 $^{a}$ | 5.66$^{a}$ | 4.95$^{b}$ | 4.88$^{b}$ | 0.634 |
| EC | 0-20 | 0.341$^{a}$ | 0.313$^{a}$ | 0.311$^{a}$ | 0.281$^{a}$ | 0.089$^{b}$ | 0.066 |
| (dSm$^{1}$) | 21-40 | 0.270$^{a}$ | 0.199$^{ab}$ | 0.196$^{ab}$ | 0.185$^{b}$ | 0.055$^{c}$ | 0.078 |
| | 41-60 | 0.149$^{a}$ | 0.119$^{a}$ | 0.120$^{a}$ | 0.124$^{a}$ | 0.037$^{b}$ | 0.053 |
| OC | 0-20 | 6.79 $^{a}$ | 5.80$^{ab}$ | 5.70$^{ab}$ | 5.389$^{b}$ | 4.72$^{b}$ | 1.15 |
| (g kg$^{-1}$) | 21-40 | 5.39$^{a}$ | 4.06$^{b}$ | 4.13$^{b}$ | 4.17$^{b}$ | 3.46$^{b}$ | 1.03 |
| | 41-60 | 3.82$^{a}$ | 2.86$^{b}$ | 2.74$^{b}$ | 2.66$^{b}$ | 2.31$^{b}$ | 0.85 |
| Av. P (mg kg$^{-1}$) | 0-20 | 96.64 | 81.12 | 104.72 | 86.25 | 72.40 | NS |
| | 21-40 | 62.69 | 53.56 | 70.06 | 56.12 | 53.13 | NS |
| | 41-60 | 44.27 | 42.09 | 45.72 | 44.66 | 37.40 | NS |
| Av. K (mg kg$^{-1}$) | 0-20 | 134.68$^{b}$ | 153.21$^{b}$ | 197.17$^{a}$ | 148.35$^{b}$ | 54.22$^{c}$ | 24.54 |
| | 21-40 | 72.5$^{bc}$ | 81.81$^{b}$ | 119.86$^{a}$ | 92.09$^{b}$ | 50.92$^{c}$ | 18.55 |
| | 41-60 | 49.08$^{b}$ | 53.61$^{b}$ | 79.98$^{a}$ | 58.15$^{b}$ | 30.60$^{c}$ | 14.24 |
| Exchangeable Ca(mg kg$^{-1}$) | 0-20 | 335.38$^{b}$ | 517.71$^{a}$ | 464.71$^{ab}$ | 322.27$^{b}$ | 195.25$^{c}$ | 112.86 |
| | 21-40 | 195.52$^{a}$ | 197.58$^{a}$ | 208.11$^{a}$ | 182.19$^{a}$ | 110.25$^{b}$ | 66.29 |
| | 41-60 | 109.73$^{a}$ | 132.31$^{a}$ | 115.06$^{a}$ | 95$^{a}$ | 63.75$^{b}$ | 31.97 |
| Exchangeable Mg (mg kg$^{-1}$) | 0-20 | 48.51$^{b}$ | 50.26$^{b}$ | 62.76$^{a}$ | 39.91$^{b}$ | 35.50$^{b}$ | 13.74 |
| | 21-40 | 22.77$^{b}$ | 27.37$^{a}$ | 32.03$^{a}$ | 22.16$^{b}$ | 19.58$^{b}$ | 4.98 |
| | 41-60 | 15.35$^{b}$ | 18.03$^{a}$ | 21.77$^{a}$ | 12.76$^{b}$ | 10.91$^{b}$ | 5.84 |
| Dehydrogenase (mg TPF/ g dry soil/ hour) | 0-20 | 3.77$^{ab}$ | 3.86$^{a}$ | 3.54$^{bc}$ | 3.36$^{c}$ | 2.13$^{d}$ | 0.30 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 21-40 | 3.10$^{a}$ | 2.80$^{ab}$ | 2.68b | 3.08$^{a}$ | 1.87$^{c}$ | 0.34 |
| | 41-60 | 2.32 $^{bc}$ | 2.43$^{b}$ | 2.02$^{c}$ | 2.75$^{a}$ | 1.59$^{d}$ | 0.30 |
| Total root biomass dry weight (g) | 0-20 | 4.11$^{a}$ | 3.56$^{a}$ | 3.34$^{a}$ | 4.05$^{a}$ | 2.36$^{b}$ | 0.942 |
| | 21-40 | 2.72$^{c}$ | 4.56$^{ab}$ | 4.41$^{ab}$ | 4.72$^{a}$ | 2.98$^{bc}$ | 1.59 |
| | 41-60 | 2.76$^{b}$ | 3.66$^{b}$ | 6.82$^{a}$ | 3.80$^{b}$ | 2.35$^{b}$ | 1.62 |
| Proportion of live roots (%) | 0-20 | 70.76$^{bc}$ | 82.48$^{a}$ | 65.80$^{c}$ | 77.39$^{ab}$ | 60.66$^{c}$ | 9.70 |
| | 21-40 | 59.46$^{cd}$ | 78.28$^{a}$ | 66.26$^{bc}$ | 72.63$^{ab}$ | 50.15$^{d}$ | 11.64 |
| | 41-60 | 87.28 $^{a}$ | 80.39$^{ab}$ | 81.27$^{bc}$ | 77.77$^{cd}$ | 59.54$^{d}$ | 15.06 |

AEU: Agro Ecological Unit
Different lowercase letters in the same row indicate significant differences ($p < 0.05$) between the treatments by Tukey's test
T1: 500g N:0P:1200g K+1Kg lime,1Kg dolomite,2kg gypsum, 2 kg NaCl, 1kg magnesium sulphate, 100gzinc sulphate, 150g borax, 25g copper sulphate
T2:T1 without NaCl
T3: T1 without gypsum
T4: T1 with Kera Probio
T5: Farmers' practice in the locality (application of 25 kg farmyard manure per palm)

**Table 2. Soil properties and root health parameters as influenced by treatments in AEU-9**

| **Soil Properties** | **Depth (cm)** | **Treatments** | | | | | **CD** |
|---|---|---|---|---|---|---|---|
| | | **T1** | **T2** | **T3** | **T4** | **T5** | **(0.05%)** |
| pH | 0-20 | 6.46$^{a}$ | 6.44$^{a}$ | 6.19$^{a}$ | 6.25$^{a}$ | 5.61$^{b}$ | 0.568 |
| | 21-40 | 5.89$^{a}$ | 5.81$^{a}$ | 5.67$^{a}$ | 5.55$^{a}$ | 5.17$^{b}$ | 0.481 |
| | 41-60 | 5.46$^{a}$ | 5.36$^{a}$ | 5.19$^{a}$ | 5.13$^{a}$ | 4.86$^{b}$ | 0.365 |
| EC (dSm$^{-1}$) | 0-20 | 0.508$^{a}$ | 0.299$^{c}$ | 0.399$^{b}$ | 0.373$^{bc}$ | 0.116$^{d}$ | 0.094 |
| | 21-40 | 0.339$^{a}$ | 0.188$^{b}$ | 0.254$^{ab}$ | 0.228$^{bc}$ | 0.081$^{c}$ | 0.088 |
| | 41-60 | 0.205$^{a}$ | 0.140$^{a}$ | 0.156$^{a}$ | 0.148$^{a}$ | 0.062$^{b}$ | 0.066 |
| OC (g kg$^{-1}$) | 0-20 | 10.4 $^{ab}$ | 10.1$^{b}$ | 12.81$^{a}$ | 12.8$^{a}$ | 9.8$^{b}$ | 2.44 |
| | 21-40 | 9.1$^{a}$ | 8.8$^{b}$ | 11.0$^{ab}$ | 11.6$^{a}$ | 8.4$^{b}$ | 2.22 |
| | 41-60 | 7.9b | 7.5$^{b}$ | 9.7$^{a}$ | 10.3$^{a}$ | 7.1$^{b}$ | 2.14 |
| Av. P (mg kg$^{-1}$) | 0-20 | 123.16$^{a}$ | 103.06$^{b}$ | 107.28$^{b}$ | 101.33$^{b}$ | 85.82$^{c}$ | 17.14 |
| | 21-40 | 77.61$^{a}$ | 50.83$^{b}$ | 55.26$^{b}$ | 42.21$^{bc}$ | 32.68$^{c}$ | 20.14 |
| | 41-60 | 43.54$^{a}$ | 20.76$^{b}$ | 23.99$^{b}$ | 23.75$^{bc}$ | 15.22$^{c}$ | 10.71 |
| Av. K (mg kg$^{-1}$) | 0-20 | 372.8a | 287.27$^{a}$ | 364.05$^{a}$ | 377.61$^{a}$ | 82.33$^{b}$ | 179.84 |
| | 21-40 | 170.8$^{b}$ | 168.34$^{b}$ | 237.17$^{b}$ | 347.73$^{a}$ | 55.20$^{c}$ | 77.09 |
| | 41-60 | 106.28$^{a}$ | 106.77$^{a}$ | 106.32$^{a}$ | 132.14$^{a}$ | 39.82$^{b}$ | 58.57 |
| Exch. Ca (mg kg$^{-1}$) | 0-20 | 595.27$^{a}$ | 587.85$^{a}$ | 550.27$^{a}$ | 503.05$^{a}$ | 278.35$^{b}$ | 206.07 |
| | 21-40 | 346.86$^{NS}$ | 452.35$^{NS}$ | 352.83$^{NS}$ | 311.82$^{NS}$ | 274.0$^{NS}$ | NS |
| | 41-60 | 252.31$^{ab}$ | 272.79$^{a}$ | 230.19$^{b}$ | 205.75$^{b}$ | 168.13$^{c}$ | 34.03 |
| Exch. Mg (mg kg$^{-1}$) | 0-20 | 85.47$^{a}$ | 87.61$^{a}$ | 88.25$^{a}$ | 81.70$^{a}$ | 30.99$^{b}$ | 37.58 |
| | 21-40 | 52.07$^{a}$ | 55.32$^{a}$ | 52.21$^{a}$ | 46.70$^{a}$ | 21.79$^{b}$ | 19.75 |
| | 41-60 | 33.55$^{a}$ | 36.67$^{a}$ | 36.78$^{a}$ | 28.37$^{ab}$ | 12.995$^{b}$ | 18.433 |
| Dehydrogenase (mg TPF/ g dry soil/ hour) | 0-20 | 3.97$^{b}$ | 4.08$^{b}$ | 4.01$^{b}$ | 7.62$^{a}$ | 2.84$^{c}$ | 1.03 |
| | 21-40 | 2.88$^{b}$ | 2.96$^{b}$ | 3.45$^{b}$ | 7.84$^{a}$ | 2.30$^{b}$ | 1.17 |
| | 41-60 | 1.89$^{b}$ | 2.53$^{b}$ | 2.85$^{b}$ | 7.00$^{a}$ | 1.81$^{b}$ | 1.06 |
| Total root biomass dry weight (g) | 0-20 | 1.37$^{bc}$ | 1.16$^{c}$ | 2.44$^{a}$ | 1.99$^{ab}$ | 1.83$^{abc}$ | 0.722 |
| | 21-40 | 3.38$^{bc}$ | 3.81$^{b}$ | 5.07$^{a}$ | 2.92$^{c}$ | 2.77$^{c}$ | 0.719 |
| | 41-60 | 3.74$^{b}$ | 3.32$^{b}$ | 2.81$^{ab}$ | 2.51$^{a}$ | 2.28a | 0.523 |
| Proportion of live roots (%) | 0-20 | 70.9$^{NS}$ | 79.3$^{NS}$ | 78.9$^{NS}$ | 72.2$^{NS}$ | 69.0$^{NS}$ | NS |
| | 21-40 | 86.0$^{a}$ | 86.2$^{a}$ | 89.0$^{a}$ | 68.7$^{b}$ | 72.0$^{b}$ | 10.9 |
| | 41-60 | 78.8$^{NS}$ | 79.0$^{NS}$ | 70.9$^{NS}$ | 83.3$^{NS}$ | 72.0$^{NS}$ | NS |

AEU: Agro Ecological Unit
Different lowercase letters in the same row indicate significant differences ($p < 0.05$) between the treatments by Tukey's test
T1: 500g N:0P:1200g K+1Kg lime,1Kg dolomite,2kg gypsum, 2 kg NaCl, 1kg magnesium sulphate, 100gzinc sulphate, 150g borax, 25g copper sulphate
T2:T1 without NaCl
T3: T1 without gypsum
T4: T1 with Kera Probio
T5: Farmers' practice in the locality (application of 25 kg farmyard manure per palm)

**Table 3. Leaf nutrient status in AEU-3 and AEU-9 as affected by the treatments**

| Treatments | N | P | K | Ca | Mg | B | Mn | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|
| | % | | | | | mg kg$^{-1}$ | | | |
| **AEU-3** | | | | | | | | | |
| T1 | 1.39 | 0.164$^{a}$ | 1.71$^{a}$ | 0.406$^{a}$ | 0.175$^{a}$ | 11.43 | 51.03$^{c}$ | 4.70 | 18.83$^{a}$ |
| T2 | 1.23 | 0.144$^{b}$ | 1.17$^{c}$ | 0.390$^{ab}$ | 0.161$^{a}$ | 11.62 | 87.72$^{a}$ | 4.39 | 14.56$^{b}$ |
| T3 | 1.28 | 0.145$^{b}$ | 1.31$^{b}$ | 0.349$^{b}$ | 0.125$^{bc}$ | 11.47 | 69.50$^{b}$ | 4.85 | 17.23$^{a}$ |
| T4 | 1. 0 | 0.144$^{b}$ | 1.31$^{b}$ | 0.352$^{b}$ | 0.140$^{b}$ | 11.56 | 53.38$^{c}$ | 5.06 | 14.78$^{b}$ |
| T5 | 1.22 | 0.138$^{b}$ | 1.04$^{c}$ | 0.289$^{c}$ | 0.122$^{c}$ | 11.37 | 32.05$^{d}$ | 4.33 | 17.37$^{a}$ |
| CD (0.05%) | NS | 0.009 | 0.129 | 0.038 | 0.017 | NS | 9.25 | NS | 1.93 |
| **AEU-9** | | | | | | | | | |
| T1 | 1.21 | 0.142 | 1.27$^{a}$ | 0.504$^{a}$ | 0.146 | 11.46$^{a}$ | 64.37$^{b}$ | 7.04$^{b}$ | 20.13 |
| T2 | 1.28 | 0.135 | 0.836$^{b}$ | 0.383$^{b}$ | 0.154 | 11.44$^{a}$ | 67.16$^{b}$ | 6.99$^{b}$ | 19.81 |
| T3 | 1.28 | 0.135 | 1.22$^{a}$ | 0.392$^{b}$ | 0.136 | 11.65$^{a}$ | 70.62$^{b}$ | 9.00$^{a}$ | 21.22 |
| T4 | 1.16 | 0.141 | 1.35$^{a}$ | 0.364$^{b}$ | 0.147 | 11.55$^{a}$ | 106.71$^{a}$ | 7.53$^{b}$ | 21.19 |
| T5 | 1.15 | 0.137 | 0.452$^{c}$ | 0.338$^{b}$ | 0.145 | 11.10$^{b}$ | 61.09$^{b}$ | 6.98$^{b}$ | 21.43 |
| CD (0.05%) | NS | NS | 0.158 | 0.065 | NS | 0.330 | 12.46 | 0.973 | NS |

AEU: Agro Ecological Unit

Different lowercase letters in the same column indicate significant differences ($p < 0.05$) between the treatments by Tukey's test

T1: 500g N:0P:1200g K+1Kg lime,1Kg dolomite,2kg gypsum, 2 kg NaCl, 1kg magnesium sulphate, 100gzinc sulphate, 150g borax, 25g copper sulphate

T2:T1 without NaCl

T3: T1 without gypsum

T4: T1 with Kera Probio

T5: Farmers' practice in the locality (application of 25 kg farmyard manure per palm)

**Table 4. Effect of treatments on microbial population**

| | General microbial Population count ( log CFU per gram dry wt. of soil) | | | | | | Function-Specific microbial Population count ( log CFU per gram dry wt. of soil) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Heterotrophic bacteria | | Filamentous fungi | | Actinomycetes | | Fluorescent pseudomonads | | Free living N fixing bacteria | |
| Treatments | 0-20 cm | 21-40 cm | 0-20 cm | 21-40 cm | 0-20 cm | 21-40 cm | 0-20 cm | 21-40 cm | 0-20 cm | 21-40 cm |
| AEU-3 | | | | | | | | | | |
| T1 | 7.35$^{a}$ | 6.66 | 4.32$^{b}$ | 4.54 | 6.30$^{c}$ | 6.01 | 1.06 | 0.00 | 6.04$^{cd}$ | 5.60 |
| T2 | 6.84 $^{c}$ | 6.32 | 4.64$^{a}$ | 4.69 | 6.46$^{b}$ | 6.22 | 2.03 | 0.83 | 5.85$^{d}$ | 5.86 |
| T3 | 7.34 $^{ab}$ | 6.49 | 4.71$^{a}$ | 4.60 | 6.28$^{b}$ | 6.00 | 0.91 | 0.91 | 6.23$^{bc}$ | 5.32 |
| T4 | 7.04$^{bc}$ | 6.45 | 4.70$^{a}$ | 4.80 | 6.74$^{a}$ | 6.30 | 0.78 | 0.00 | 6.38$^{ab}$ | 5.52 |
| T5 | 7.24 $^{ab}$ | 6.39 | 4.19$^{b}$ | 4.34 | 6.42$^{bc}$ | 6.28 | 0.00 | 0.00 | 6.47$^{a}$ | 5.48 |
| CD (0.05) | 0.266 | NS | 0.242 | NS | 0.149 | NS | NS | NS | 0.210 | NS |
| AEU-9 | | | | | | | | | | |
| T1 | 6.80 | 6.72 | 4.99$^{b}$ | 4.57$^{c}$ | 6.38$^{b}$ | 6.41 | 0.77 | 0.67 | 6.43$^{a}$ | 6.2$^{b}$ |
| T2 | 6.99 | 6.4 | 5.14$^{b}$ | 4.89$^{b}$ | 6.72$^{a}$ | 6.21 | 0.00 | 0.00 | 6.07$^{b}$ | 5.72$^{c}$ |
| T3 | 6.39 | 6.26 | 5.43$^{a}$ | 5.41$^{a}$ | 6.04$^{c}$ | 6.16 | 0.00 | 1.55 | 6.21$^{b}$ | 6.78$^{a}$ |
| T4 | 7.20 | 6.89 | 5.11$^{b}$ | 4.98$^{b}$ | 6.49$^{b}$ | 6.45 | 0.83 | 0.00 | 6.29$^{ab}$ | 6.0$^{b}$ |
| T5 | 6.82 | 6.21 | 5.59$^{a}$ | 5.01$^{b}$ | 6.06$^{c}$ | 6.19 | 0.00 | 1.79 | 5.82$^{c}$ | 6.0$^{b}$ |
| CD (0.05) | NS | NS | 0.198 | 0.240 | 0.201 | NS | NS | NS | 0.224 | 0.23 |

AEU: Agro Ecological Unit

Different lowercase letters in the same column indicate significant differences ($p < 0.05$) between the treatments by Tukey's test. T1: 500g N:0P:1200g K+1Kg lime,1Kg dolomite,2kg gypsum, 2 kg NaCl, 1kg magnesium sulphate, 100gzinc sulphate, 150g borax, 25g copper sulphate

T2:T1 without NaCl

T3: T1 without gypsum

T4: T1 with Kera Probio and T5: Farmers' practice in the locality (application of 25 kg farmyard manure per palm)

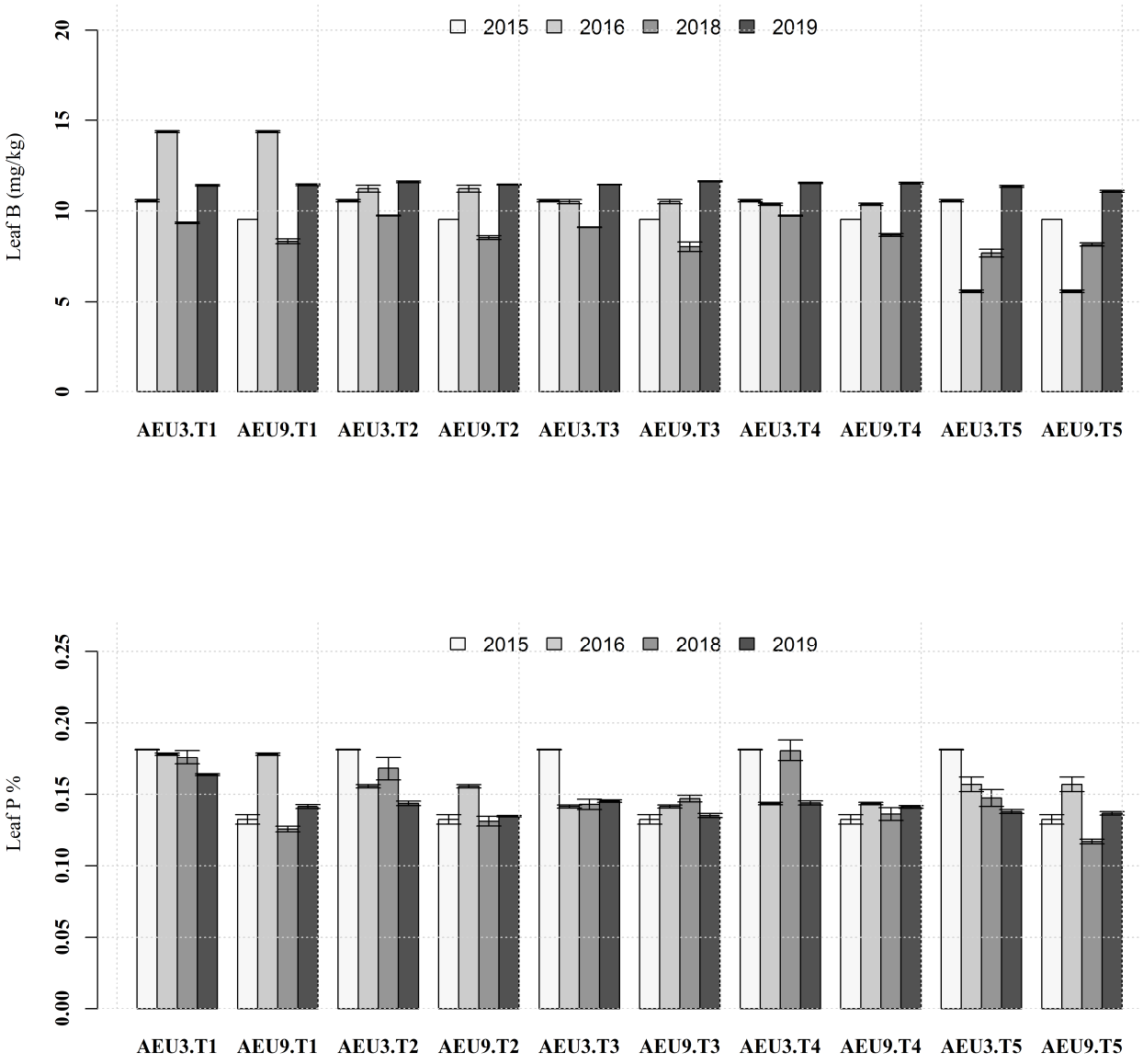


**Figure 1(a). Leaf nutrient concentration over the years (a and b)**

**Figure 1(b). Leaf nutrient concentration over the years**
**(b:Leaf P and B)**

T1: Application of 500g N, 0P, 1200g K, 1kg lime, 1kg dolomite, 2kg gypsum, 2 kg NaCl, 1kg magnesium sulphate, 100g zinc sulphate, 150g borax, and 25g copper sulphate.

T2: T1without NaCl. T3: T1without gypsum. T4: T1 with Kera Probio T5: Farmers' practice in the locality (application of 25 kg farmyard manure per palm)

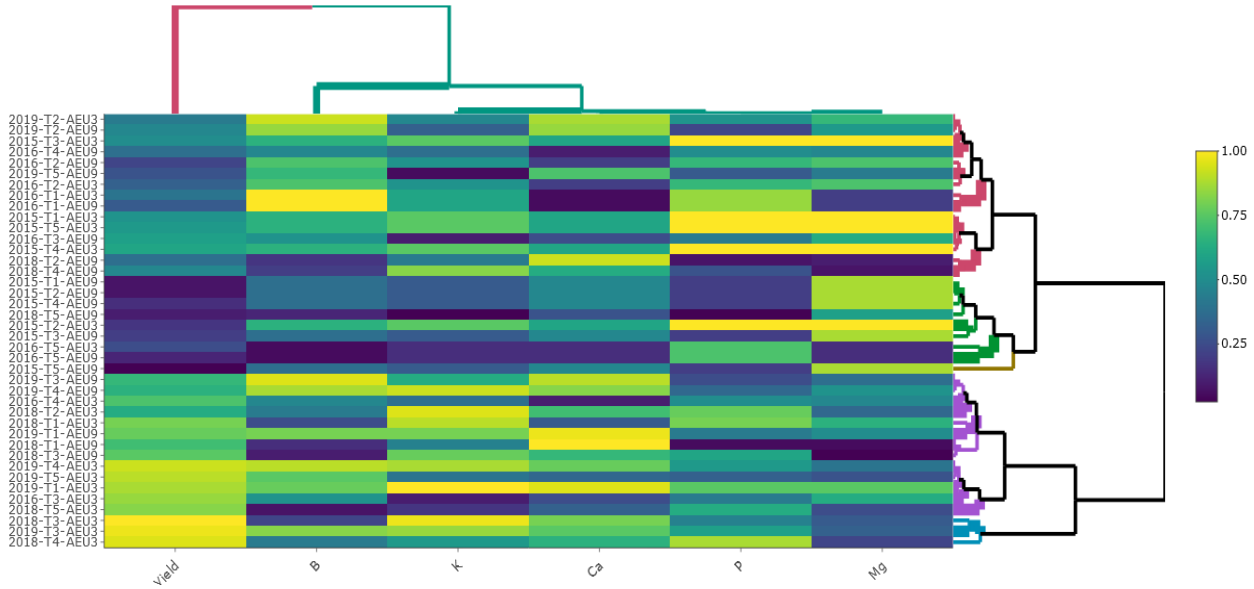


**Figure 2. Heatmap depicting Spearman's rank correlation coefficients, visually representing strength and direction of monotonic relationships between leaf nutrient concentrations (-Ca, K, Mg, B, and P) through colour intensity and gradients. It uses colour gradients to indicate the correlation coefficients, where darker shades often denote stronger correlations, while lighter shades indicate weaker or no correlations.**

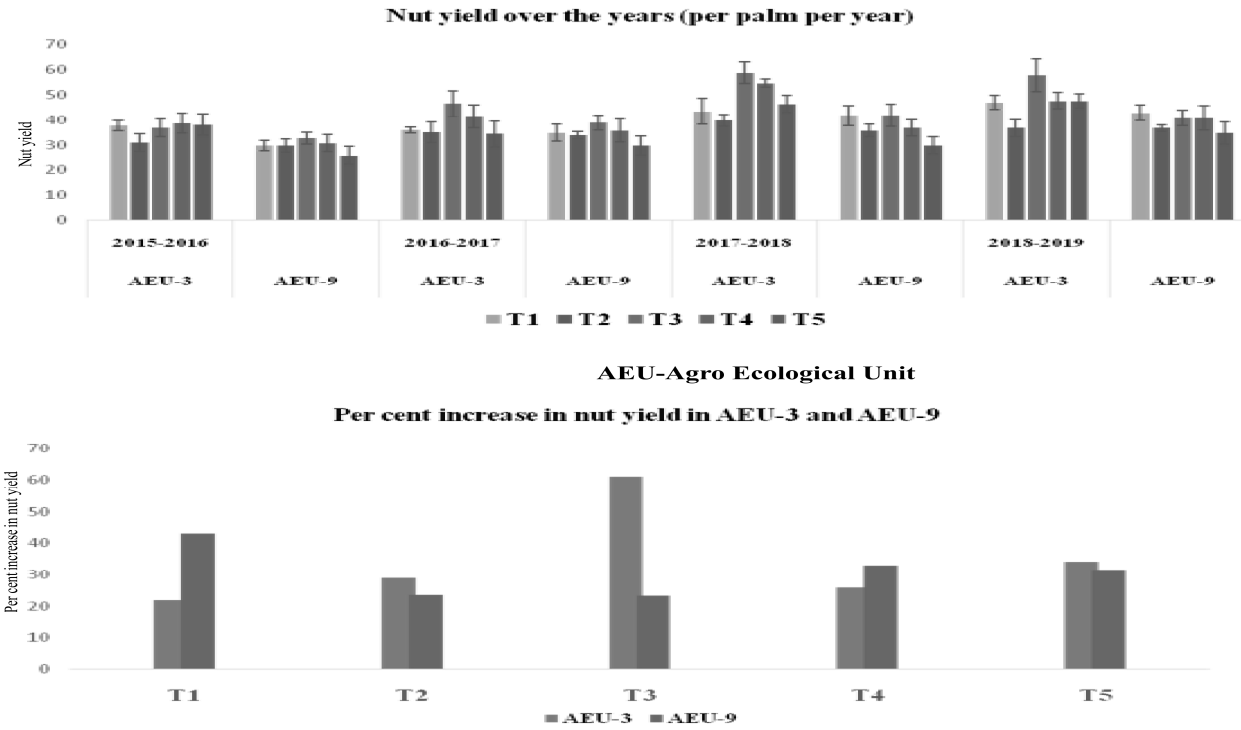


**Figure 3. Nut yield and per cent increase in yield over the years**

T1: Application of 500g N, 0P, 1200g K, 1kg lime, 1kg dolomite, 2kg gypsum, 2 kg NaCl, 1kg magnesium sulphate, 100g zinc sulphate, 150g borax, and 25g copper sulphate.

T2: T1without NaCl. T3: T1without gypsum. T4: T1 with Kera Probio T5: Farmers' practice in the locality (application of 25 kg farmyard manure per palm)

**S 1. Methods of analysis of soil samples and plant samples**

| Sl. No. | Estimation | Method | Reference |
|---|---|---|---|
| **Soil Parameters** | | | |
| 1. | Mechanical analysis (soil texture) | International pipette method | Piper (1966) |
| 2. | | Physico-chemical properties | |
| | a. EC | Potentiometry | Jackson (1973) |
| | b. pH | Conductometry | Jackson (1973) |
| 3. | Chemical properties | | |
| | a. Organic Carbon | Chromic acid wet digestion method | Walkley and Black (1934) |
| | b. Available P | Bray and Kurtz extraction method using 0.03N Ammoniumflouride and 0.025N HCl | Jackson (1973) |
| | c. NN $NH_4OAc$-K | Neutral Normal $NH_4OAc$ using flame photometer | Standford and English (1949) |
| | d. Calcium | Neutral Normal $NH_4OAc$ using AAS | Standford and English (1949) |
| | e. Magnesium | Neutral Normal $NH_4OAc$ using AAS | Standford and English (1949) |
| | f. Micronutrients Cu, Zn, Fe, Mn | Extraction using 0.1N HCl and estimation using Atomic Absorption Spectrophotometer | Lindsay and Norvell (1978) |
| | g. Boron | Hot water extraction method | Berger and Truog (1939) |
| Plant Parameters | | | |
| 1. | Nitrogen | Microkjeldahl method | Humphries (1956) |
| 2. | Tri acid extract | Nitric acid, Sulphuric acid and Perchloric acid 9:2:1 ratio | Piper (1966) |
| 3. | Phosphorus | Vanadomolybdate yellow colour method | Jackson (1973) |
| 4. | Potassium | Flame photometry | Stanford and English (1949) |
| 5 | Calcium | Atomic Absorption Spectrophotometry | Stanford and English (1949) |
| 6 | Magnesium | Atomic Absorption Spectrophotometry | Stanford and English (1949) |
| 7 | Sulphur | Nitric – perchloric acid (9 : 3) digestion and turbidemetry | Tabatabai and Bremner (1970) |
| 8 | Micronutrients Cu, Zn, Fe, Mn | Nitric – perchloric acid (9 : 3) digestion and Atomic Absorption spectrophotometry | Lindsay and Norvell (1978) |
| 9 | Boron | Azomethine –H colorimetric method | Bingham (1982) |

**S 2. Soil fertility parameters and leaf nutrient content at the experiment sites of AEU-3 and AEU-9**

| Soil Parameters | AEU-3 | | | AEU-9 | | | Foliar nutrients | AEU-3 | AEU-9 |
|---|---|---|---|---|---|---|---|---|---|
| | 0-20 | 21-40 | 41-60 | 0-20 | 21-40 | 41-60 | | | |
| | Cm | | | | | | | | |
| | Soil Data | | | | | | | | |
| pH | 5.38± 0.135 | 5± 0.130 | 4.94± 0.118 | 4.96± 0.133 | 4.62± 0.069 | 4.49± 0.079 | | | |
| EC ($dSm^{-1}$) | 0.16± 0.032 | 0.11± 0.038 | 0.08± 0.043 | 0.149± 0.056 | 0.073± 0.048 | 0.073± 0.062 | Leaf Nutrient content | | |
| Organic carbon ($g\ kg^{-1}$) | 8.6± 0.065 | 7.2± 0.052 | 4.9±0.09 | 8.2±0.085 | 6.3±0.063 | 5.1± 0.063 | N (%) | 1.24±0.024 | 1.32±0.004 |
| Available P ($mg\ kg^{-1}$) | 52.88± 2.97 | 44.2±4 .79 | 49.83± 6.73 | 111.66± 7.05 | 14.33± 2.79 | 6.76± 2.58 | P (%) | 0.142±0.001 | 0.13±0.009 |
| Available K ($mg\ kg^{-1}$) | 66.11± 13.20 | 57.72± 9.58 | 43.5± 5.28 | 45.93± 8.35 | 39.76± 10.59 | 51.94± 11.54 | K (%) | 1.23±0.010 | 0.84±0.008 |
| Available Ca ($mg\ kg^{-1}$) | 256.91± 23.24 | 214.19± 23.77 | 196.27±18.06 | 302.39± 10.78 | 221.97± 13.91 | 165.94± 11.73 | Ca (%) | 0.30±0.004 | 0.297±0.005 |
| Available Mg ($mg\ kg^{-1}$) | 66.13± 9.25 | 45.39± 8.35 | 32.27± 6.51 | 37.05± 4.69 | 31.74± 4.17 | 16.78± 0.18 | Mg (%) | 0.19±0.004 | 0.19±0.006 |
| Fe ($mg\ kg^{1}$) | 36.85± 2.55 | 47.23± 3.12 | 43.45± 3.66 | 19.73± 6.42 | 11.3± 4.12 | 8.33± 4.48 | Fe (mg/kg) | 156.58±0.326 | 130.9±0.512 |
| Mn ($mg\ kg^{-1}$) | 9.91± 1.66 | 7.24± 0.946 | 6.36± 0.843 | 9.72± 2.05 | 3.72± 0.163 | 4.16± 0.321 | Mn (mg/kg) | 51.29±0.410 | 51.31±0.022 |
| Cu ($mg\ kg^{-1}$) | 0.87± 0.060 | 0.87± 0.081 | 0.79± 0.086 | 0.799± 0.128 | 0.293± 0.047 | 0.195± 0.020 | Cu (mg/kg) | 5.9±0.125 | 4.88±0.022 |
| Zn ($mg\ kg^{-1}$) | 4.06 ±0.676 | 4.84± 0.519 | 8.67± 0.663 | 3.12± 0.071 | 1.3±0.578 | 1.57± 0.482 | Zn (mg/kg) | 15.51±0.204 | 17.85±0.004 |
| B ($mg\ kg^{-1}$) | 0.5 ±0.013 | 0.49± 0.012 | 0.47± 0.012 | 0.77± 0.698 | 0.25± 0.023 | 0.22± 0.015 | B (mg/kg) | 10.56±0.157 | 9.56±0.005 |

AEU-Agro Ecological Unit

Data represents means ± standard error ($n = 12$).

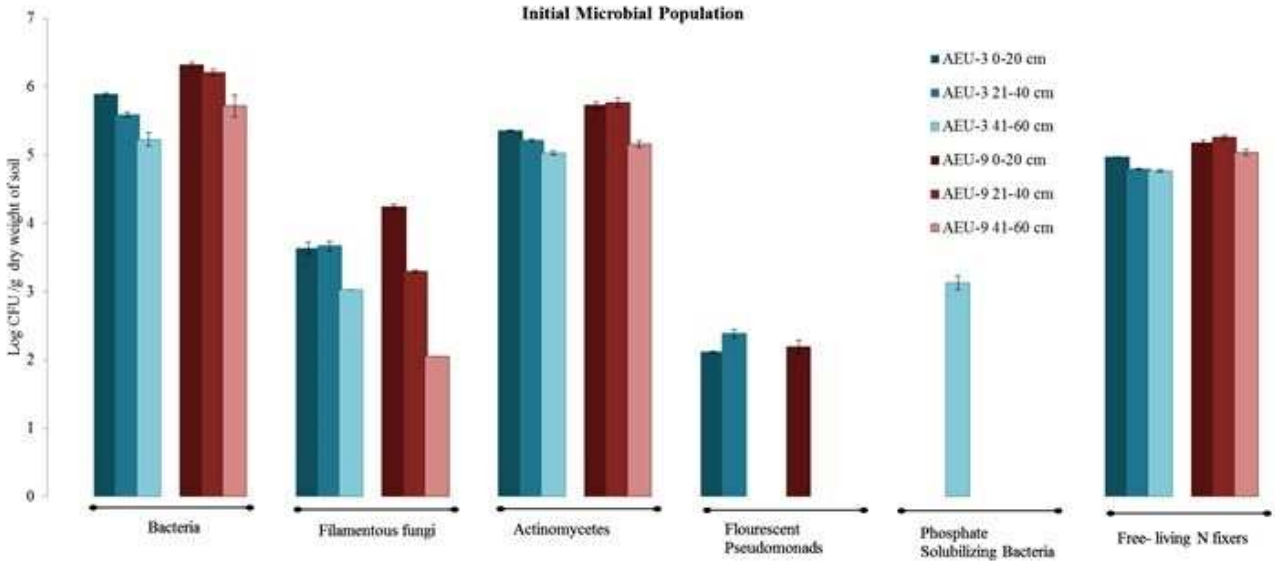


**Figure S3. Initial soil microbial population at the experiment sites of AEU-3 and AEU-9**

## DISCUSSION

The systematic provision of essential nutrients is an absolute pre-requisite for managing soil constraints and improving the productivity of coconut palms. However, the added nutrients and amendments may result in a differential response in the nutrient dynamics of soil, leaf, and palm yield. In AEU-9, treatments positively influenced soil pH, organic carbon, and exchangeable bases such as K, Ca, and Mg. The increase in the sandy soil pH can be primarily attributed to the addition of 1 kg of lime and dolomite. The favourable soil reaction facilitated microbial growth, organic matter decomposition, and improvement in soil organic carbon. The improvement in organic carbon content in the sandy soil of AEU-3 was deemed insignificant compared ~~to~~ with the baseline value, indicating that apart from in situ palm residue recycling, external organic inputs are critical to maintain the necessary level of organic matter in sandy soils. Treatment without gypsum (T3) showed higher Mg and K content, while gypsum addition resulted in the downward displacement of Mg and K, with Mg being predominantly affected. This effect was more pronounced in light sandy soils (Anderson *et al.,* 2021) and warrants the omission of gypsum applications for the amelioration of subsoil acidity in sandy soils. If applying gypsum is necessary for the correction of subsoil acidity, K and Mg supplementation must be ensured to avoid the deficiency of these nutrients. However, Ca content after the treatments showed improvement compared ~~to~~ with the pre-treatment.

Significant improvement in pH were observed at three depths in the south-central laterite soils of AEU-9. The effectiveness of lime and phosphogypsum in ameliorating soil acidity in lateritic soils with high iron content was determined by Joseph *et al*. (2020). The downward displacement of cations in AEU-9 was relatively small compared with AEU-3. Organic carbon content in laterite soils (AEU-9) improved over the initial value with the highest percentage improvement in T4 at all three depths. The in-situ recycling of palm residues combined with the bioinoculant Kera Probio within the basin significantly improved the organic carbon content in the treated (Chatterjee *et al.,* 2017; Milh *et al*., 2016). Higher dehydrogenase activity in the laterite soils of AEU-9 and the profuse earthworm castings corroborated the improved organic matter status.

Analysing foliar nutrient concentration is an efficient method for assessing the fertilisation efficiency in coconut (Saldanha *et al.,* 2017). The leaf nutrient status was improved regarding all the nutrients compared to the initial nutrient status in 2015 in sandy and laterite soils. Palms in the control plots showed deficient levels of K and Mg, confirming need for nutrients application for adequate foliar nutrient levels. The systematic provision of major nutrients improved the nutrient concentration in coconut palm leaves, as reported elsewhere by Shinde *et al.,* (2021). A steady rise in leaf K concentration in AEU-3 throughout the years was observed for T1. Uptake was also facilitated by the presence of more live roots in the lower depths in T1. In contrast, other treatments showed a smaller percentage increase over the years. In T5, the content gradually declined below the critical level of K concentration as proposed by IRHO (1989). The leaf P content in sandy soil showed a steady decline evidently due to the non-addition of phosphatic fertilisers coupled with the leaching in sandy soils. Such a declining of

foliar nutrients in coconut trees was validated in the studies of Rubio *et al.,* (2023). In AEU-9, the highest percentage increase in leaf K (60.91%) was observed in T4 with the application of Kera Probio followed by T1 (51%).

Leaf Mg gradually declined, most likely due to the antagonism between Ca and Mg (Holland *et al.,* 2018; Vanitha and Indrani, 2019; Lins *et al.,* 2021). Reduction in the foliar Mg levels may be attributed to its preferential uptake of K, being an oilseed crop, coupled with the reduced levels of Mg in the soil. Owing to the continuous Ca supply through lime, dolomite, and gypsum sources, the antagonistic interaction was pronounced in both AEUs. Further, K and Ca concentrations in the leaves increased steadily, which can negatively affect foliar Mg levels. The treated palms still maintained a sufficient range, likely due to the 1 kg magnesium sulphate supply. In AEU-9, T1 exhibited the highest percentage increase in leaf Ca (69.9%), while the lowest increase was observed in T5. In AEU-9, a 21% increase in B over the pre-treatment was observed in T3. Nevertheless, the content in the soil and coconut palm leaves improved by applying 160 g borax in four splits after correcting the soil reaction in sandy soils (Mathew *et al.,* 2018).

The positive effects of treatments on enhancing soil health parameters were reflected in soil dehydrogenase activity in sandy (AEU-3) and laterite soils (AEU-9). Factors such as soil moisture, aeration status, oxidation-reduction potential, pH, organic matter content, depth of the soil profile, soil temperature, and soil inherent fertility status contribute to the activity of soil dehydrogenase (Reddy *et al.,* 2020). Laterite soil has higher clay content and comparatively higher moisture-holding capacity, which both can lead to organic matter solubilisation, leading to the build-up of dehydrogenase activity in laterite soil compared to sandy soil. The high dehydrogenase activity observed in the laterite soil treated with Kera Probio (T4) was likely due to greater microbial activity, a direct indicator of soil biological health which are responsible for organic matter degradation, reflected in soil respiration and the release of carbon dioxide from the rhizosphere (Zhang *et al.,* 2010; Zhang *et al*., 2013). Kera Probio was effective in laterite soil indicating that more organics are required in sandy soil for higher microbial activity through Kera Probio application.

Soil microbiota and their function in agro ecosystems are largely formulated by edaphic soil properties, agronomic management and fertiliser regimes. Variations in soil pH, organic matter, electrical conductivity, aluminium concentration (Nair *et al.,* 2018) and pedological conditions formed the prime determinants (Degrune *et al.,* 2019) for the distinctive microbial communities in the two AEUs. The compaction of lateritic soils with increasing depths in AEU-9 can be attributed to the significant decrease in the aerobic mycelial-forming microorganisms, including fungi and actinomycetes. Actinomycetes, a widely found group of microorganisms in agricultural soils, strongly influenced soil health. The relative abundance of actinobacteria in soils with a higher pH (Lauber *et al*., 2009) and mineral-fertilised soils (Francioli *et al.,* 2016) would substantiate the results derived in this experiment. Long-term fertilisation is positively associated with the relative abundance of facultative nitrogen fixers, such as *Bradyrhizobium* and *Burkholderia*, often classified as copiotrophs without any correlation with N-fixing rates (Fan *et al*., 2019). Regulation of soil microbial composition by changes in elemental stoichiometry (C: N: P) after N fertilisation (Shen *et al.,* 2019) mostly influencing upper soil layers, would also be a possible explanation. Variation in the phosphate solubilising phenotype under high P stress and the repression of P solubilizers in soils with high available P was reported by Gyaneshwar *et al*. (2002).

The enhanced soil and leaf nutrient status resulted from the addition of soil amendments and nutrients improved coconut productivity. Magnesium and K are critical nutrients for coconut production; their displacement by adding gypsum in T1 and T2 might have reduced yield in all other treatments compared to that of T3 without gypsum application. Improved yield of T3 in AEU-3 emphasised the critical role of Mg on the yield and productivity of coconut palms. The influence of Mg on coconut yield was also described by Lins *et al*. (2021). Also, the significant role of enhanced availability of K and B would have been reflected in the nut yield of coconut palms. The positive role of K and B in enhancing the yield characteristics of coconut in the *Terai* region was observed by Babu *et al.,* (2021). The positive influence of added fertilisers on the enhancement of coconut yield and productivity was recorded by Malhotra *et al*. (2017). Root health observations in both AEUs also indicated the positive influence of amendments and nutrients. The difference in soil environment as a factor for the variations in root biomass was indicated by Carvalho *et al*. (2024).

In present study, it was hypothesised that the addition of amendments and nutrients could enhance the soil and foliar nutrient and improvement in the nut yield. But the results indicated differential response to nutrients and amendments in both land use systems. Even though, gypsum was applied to ameliorate sub soil acidity, in sandy soils, it resulted in the greater displacement of Mg and K to the lower layers. Hence our study points towards stringent selection of ameliorants based on soil properties.

**Conclusion:** Nutrient dynamics in the soil and leaves of coconut palms were significantly influenced by the scheduled treatments comprising the major secondary nutrients and micronutrients. The treatment effect was

different in sandy and laterite soils in terms of the differential leaching of cationic nutrients, organic carbon content and soil dehydrogenase activity. Sandy soils require application of inputs as per T3 (T1 without gypsum), with external organic inputs and palm residues whereas in laterite soils application of treatments as per T1 is required with in situ palm residue recycling. Our results established that soil and palm health could be maintained and improved through treatments with minimal cultural operations. Hence, a judicious combination of chemical fertilisers and amendments along with palm residues, depending on the soil type, is an impetus for achieving sustainable palm production and maintaining the balance of the soil ecosystem. Further studies in this area may establish the relationship between enhancing palm health in terms of resistance to pests and diseases and nutrient dynamics in the soil and plants of coconut ecosystem.

**Acknowledgement:** The authors sincerely acknowledge Kerala State Planning Board for funding the research.

**Statements and Declarations**

**Compliance with ethical standards**

**Conflict of interest**: The authors declare that they have no conflict of interest.

**Data Availability:** The data presented in this study is available on request from the corresponding author.

**Author contribution statement**: KMN formulated the project. JM and AAH performed the experiment, SI did microbial analysis. SS performed the statistical analysis. VKK and RB-edited the manuscript. All authors revised and approved the manuscript.

## REFERENCES

Anderson, C.G., H.J.M.D Pathan., R. Sharma and J. Easton (2021). Gypsum applications on acid soils in a water limited environment: Solution Chemistry. Agronomy 11:826. https://doi.org/10.3390/agronomy11050826

Babu, N.S., P. S.Medda., H. Bhattacharjee., A.K. Sinha and A. Ghosh (2021). Leaf boron and potassium and nut weight in coconut (*cocos nucifera* L.) as affected by their individual and combined applications. Int. J. Curr. Microbiol. App.Sci.10:919-927 https://doi.org/10.20546/ijcmas.2021.1002.108

Berger, K.C. and R. Truog (2021). Boron determination in soils and plants, *Ind. Eng. Chem. Anal. Ed.* 11, 10, 540-545 https://doi.org/10.1021/ac50138a007

Bingham, F.T. (1982). Boron. In methods of soil analysis, Part 2, 2nd edition. Page AL (Eds.)No.9. American Society of Agronomy and Soil Science Society of America, Madison, WI.pp431-448

Carvalho, J.I., M.B. Caraygan., N.T.L Tran., O.J. Hernandez ., W.B. Youn.,Y.J. An. and B.B. Park (2024). Variation in root biomass and distribution based on the topography, soil properties, and tree influence index: The Case of Mt. Duryun in Republic of Korea. Plants 13: 1340 https://doi.org/10.3390/plants13101340

Casida, L.E.Jr., D.A. Klein and T. Santoro (1964). Soil dehydrogenase activity. Soil Sci. 98:371-376.DOI: 10.1097/00010694-196412000-00004

Chatterjee, R., S. Gajjela and R.K. Thirumdasu (2017). Recycling of organic wastes for sustainable soil health and crop growth. International J. Waste Resources. 7:3 DOI: 10.4172/2252-5211.1000296

Coconut Development Board (2020). Area production and productivity of coconut in India. Statistics

Degrune, F. F. Boeraeve., M. Dufrêne., J.T. Cornélis., B. Frey and M. Hartmann (2019). The pedological context modulates the response of soil microbial communities to agro ecological management. Front. Ecol. Evol. 7:261. doi: 10.3389/fevo.2019.00261

Fan, K., M. Delgado-Baquerizo., X.D. Wang., Y.Wu., W.Zhu., F. Yu., Y. Zhu and H. Chu (2019). Suppressed N fixation and diazotrophs after four decades of fertilization. Microbiome 7: 143. https://doi.org/10.1186/s40168-019-0757-8

Francioli, D., E.Schulz., G. Lentendu., T. Wubet., F. Buscot., T. Reitz (2016). Mineral vs. organic amendments: microbial community structure, activity and abundance of agriculturally relevant microbes are driven by long-term fertilization strategies. Front. Microbiol. 7:1446. doi: 10.3389/fmicb.2016.01446

Fremond, Y. (1964).The contribution of IRHO to the study of mineral nutrition of the coconut palm. *In:* Proc. Second Sessn. FAO Tech. Wkg. Pty. Cocon. Prod. Prot. & Process. Colombo, Sri Lanka

Gomez, K..A. and A.A. Gomez (1984). Statistical procedures for agricultural research (2 ed.). John Wiley and sons, New York p. 680

Gyaneshwar, P., G.N. Kumar., L.J. Parekh., P.S.Poole (2002). Role of soil microorganisms in improving P nutrition of plants. Plant soil. 245:83–93. https ://doi.org/10.1023/A:1020663916 259

Holland, J.E., A.E. Bennett., A.C. Newton., P.J. White., B.M. McKenzie., T.S. George., R.J. Pakeman., J.S. Bailey., D.A.Fornara and R.C. Hayes (2018).Liming impacts on soils, crops and biodiversity in the UK: A review, Science of the

Total Environ 316–332 https://doi.org/10.1016/j.scitotenv.2017.08.020

Humphries, E.C (1956). Mineral components and ash analysis. Modern methods of plant analysis, Vol. 1, Springer-Verlag, Berlin pp. 465-502

IBM Corp (2016).SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp.

IRHO- Institut de Recherches Pour les Huiles et Oléagineux. Rapport d'activité. (1989). Oléagineux, Paris v.44, p.1- 22

Jackson, M. L (1973). Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi, p.498 (1973).

Joseph, B., R. Gladis., B. Aparna and J.S.Bindhu (2020). Assessment of iron toxicity in lateritic wetland soils of Kerala and management using non-conventional sources of lime. Int. J. Curr. Microbiol.App.Sci.9:2139-2148. https://doi.org/10.20546/ijcmas.2020.905.244

Khan, H.H. and V. Krishnakumar (2018). Soil productivity and nutrition. In: Nampoothiri, K.UK, Krishnakumar V, Thampan PK., Nair MA. (Eds.). The coconut palm (*Cocos nucifera* L.) -- Research and Development Perspectives.pp.323-442

Lauber, C.L., M. Hamady., R. Knight., R and N. Fierer (2009).Pyrosequencing-based assessment of soil pH as a predictor of soil bacterial community structure at the Continental scale. Appl. Environ. Microbiol. 75: 5111–5120.doi:10.1128/AEM.00335-09

Lindsay, W.L and W.A. Norvell(1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Science Society of America J, 42: 421-428 doi.org/10.2136/sssaj1978. 03615995004200030009x

Lins, P.M.P., M.J.I. Viegas and O.Ferreira (2021). Nutrition and production of coconut palm cultivated with mineral fertilization in the state of Pará. Revista Brasileira de fruticultura.43:1-15 doi: http://dx.doi.org /10.1590/0100-29452021113

Malhotra, S.K., H.P. Maheshwarappa., V. Selvamani., P. Chowdappa (2017). Diagnosis and management of soil fertility constraints in coconut (*Cocos nucifera* L.): A review. Indian J. Agric. Sci 87: 711–26 http://krishi.icar.gov.in/jspui/handle/123456789/13424

Mathew J., V. Krishnakumar., V. Srinivasan.,R. Bhat., N. Namboothiri and A. A Haris (2018). Standardization of critical boron level in soil and leaves of coconut palms grown in a tropical Entisol. *J.Soil Science and Plant Nutrition*. 18 (2):376-387 http://dx.doi.org/10.4067/S0718-95162018005001203

Mathew, J., A.A Haris., R. Bhat., V. Krishnakumar., K. Muralidharan, K..S. John and U. Surendran (2021).A comparative assessment of nutrient partitioning in healthy and root (wilt) disease affected coconut palms grown in an Entisol of humid tropical Kerala. Trees 35:621-635 doi 10.1007/s00468-020-02064-w

Mathew, J., A.A. Haris S. Indhuja., K.M., V.Krishnakumar., V., R. Bhat. And K.S. Anilkumar (2022).Effectiveness of site specific management practices on the amelioration of soil acidity in the entisols and ultisols of humid tropics. J.Soil Science and Plant Nutrition. 22: 1060-1073.doi 10.1007/s42729-021-00715-6 9

Menon, K.P.V. and K.M. Pandalai (1958).The Coconut Palm- A Monograph. Indian Central Coconut Committee. p.384

Milh, R., R. Bol., W. Amelung and N. Brahim (2016). Soil organic matter amendments in date palm groves of the Middle Eastern and North African region: a mini-review". J. Arid Land.8: 77-92. DOI: 10.1007/s40333-015-0054-8

Nair, K.M., A.A.Haris., J. Mathew.,V. Srinivasan., R. dinesh., H.Hamza., P. Subramanian., C.Thampan., K.P. Chandran., V. Krishnakumar.,R. Bhat., R. Hegde and S.K. Singh (2018) .Coconut-growing soils of Kerala: 2. Assessment of fertility and soil related constraints to coconut production. J. Plantation Crops 46: 84-91. doi: 10.25081/jpc.2018.v46.i2.3719

Nair, K.M.,A.A. Haris., J. Mathew., V. Srinivasan., R. Dinesh., H. Hamza., P. Subramanian., C. Thampan., K.P. Chandran., V. Krishnakumar., R. Bhat., R. Hegde and S. K. Singh (2018b).Coconut-growing soils of Kerala: 2. Assessment of fertility and soil related constraints to coconut production. J. Plant. Crops. 46: 84-91. https://doi.org/ 10.25081/jpc.2018.v46.i2.3718

Pelczar, M.J Jr., R.C. Bard., G.W. Burnett.,H.J. Conn., R.D. Demoss., E.E. Euans., F.A. Jennison., M.W. Meckee A.P.,A.J. Riker., J. Warren., O.B. Weeks (1957).Manual of microbiological methods. McGraw Hill Book Company Inc, New York

Piper, C.S. (1966). Soil and Plant Analysis. Hans Publisher, Bombay

Reddy, B.S., M.S. Nagaraja., B.C. Mallesha and G.G. Kadallii (2020).Enzyme activities at varied soil organic carbon gradients under different land use systems of Hassan district in Karnataka. Int. J. Curr. Microbiol. App. Sci 9: 1739-1745 https://doi.org/10.20546/ijcmas.2020.903.201

Rubio, E.E.S., M.C. Rios G.J.H. Cool., J.H.R. Silva., M.D.C.Z. Cordoba and M.F. Rayes

(2023).Nutrient composition of yellow Malayan dwarf coconut trees (*cocos nucifera* L.) leaf using green manures. Int. J. Advanced Res.11:1278-1283 doi:10.21474/IJAR01/16144

Saldanha, E.C.M., M.L.S. Junior., P.M.P.Lins., S.C.C. Farias and P.G.S. Wadt (2017). Nutritional diagnosis in hybrid coconut cultivated in northeastern Brazil through Diagnosis and Recommendation Integrated System (DRIS). Revista Brasileira de Fruticultura, Jaboticabal. 39:1-9

Shen, F., J. Wu., H. Fan., W. Liu., X. Guo., H. Duan., H., L. Hu and X. Wei (2019).Soil N/P and C/P ratio regulate the responses of soil microbial community composition and enzyme activities in a long-term nitrogen loaded Chinese fir forest. Plant Soil 436: 91–107 https://doi.org/10.1007/s11104-018-03912-y

Shinde, V.V., S. Sumitha and H.P. Maheshwarappa (2021).Soil fertility properties, leaf nutrient status and yield of coconut and intercrops as influenced and coconut based cropping system in coastal plains of western India Bangladesh J.Bot.50 (4):1067-1075 DOI: https://doi.org/10.3329/bjb.v50i4.57074

Standford, S. and L. English (1949).Use of flame photometer in rapid soil tests for K and Ca. Agron J 41: 446 – 447. doi.org/10.2134/agronj1949.00021962004100090012x

Tabatabai, M.A. and J. M. Bremner (1970). Arylsulfatase activity of soils. Soil Science Society of America J. 34: 225-229

Vanitha, P. and R. Indirani (2019). Synergistic and antagonistic interactions of calcium with other nutrients in soil and plants. http://dx.doi.org/10.2139/ssrn.3503225

Zhang, N., X.He., Gao, Y., Y. Li., H. Wang., D. Ma., R. Zhang. And S. Yang (2010). (2010). Pedogenic carbonate and soil dehydrogenase activity in response to soil organic matter in artemisia ordosica community. Pedosphere 20 pp. 229-235 https://doi.org/10.1016/S1002-0160(10)60010-0

Zhang, J., H.G. Yun., B.C. Zhang., J.J.L. Yang., Y.X.X.Yang and H.X.J. Dai (2013). Biological properties of lateritic red soil and their relationships with soil fertility in Southern China under different land use types 24:3423-343