***Original Research Article***

**Effect of Eucalyptus based agroforestry systems on soil properties in different land use patterns in Upper-Gangetic Plains of Uttar Pradesh,India**

**Abstract**

The present study was conducted during kharif season 2022 and 2023 at the Padila Nursery, Indian Council of Forestry Research and Education, Eco-Rehabilitation Centre, Prayagraj, U.P. to compare the distribution of chemical properties and nutrient status of soil in two different depths under seven land use systems *viz*., T1:Eucalyptus+Mentha+Tulsi, T2:Eucalyptus+Mentha, T3:Eucalyptus+Tulsi, T4:Eucalyptus Sole, T5:Mentha+ Tulsi Sole, T6:Mentha Sole and T7:Tulsi sole. Before transplanting of the medicinal plants (mentha and tulsi) and after harvesting, the soil sampling was performed to determine the soil parameters like organic carbon and the minerals content. Eucalyptus based agroforestry system performed better as compared to sole crop in respect of various soil chemical properties and available nutrients status in soil at different soil depths. Nitrogen, phosphorus, potassium content and organic carbon were higher in the agroforestry system as compared to the open farming system. In both experimental year, the average maximum available N, P, K and organic carbon at 0-15 cm (240.23 kg/ha, 28.85 kg/ha, 135.53 kg/ha and 0.88 gm/kg respectively) and 15-30 cm (227.07 kg/ha, 25.35 kg/ha, 125.52 kg/ha and 0.55 gm/kg respectively) was observed in T3: Eucalyptus + Tulsi. A high soil pH was found in an open farming system and lower pH in an agroforestry system. The maximum soil pH for both experimental year was found in the T5: Mentha + Tulsi Sole with the average value of 7.62 in 0-15cm depth and 7.67 in 15-30 cm depth. Overall, this study determines the effect of eucalyptus based agroforestry systems on soil nutrients.

**Keywords**: Agroforestry, Eucalyptus, nutrient status, soil depth, soil properties

**INTRODUCTION**

Agroforestry systems (AFS) are regarded as a universal solution to the challenges of intensive agriculture. The diversification of land use through AFS is an essential strategy to meet society's multiple needs without compromising the agro-ecosystem. In AFS, the careful selection of tree and crop species helps prevent land degradation, improve soil productivity, enhance land sustainability, and increase resource use efficiency. A major benefit of agroforestry systems is the overall increase in production through improved soil fertility (Singh, 2010). These systems contribute to carbon sequestration, maintain soil productivity by reducing soil erosion, and improve salt-affected soils by lowering the water table. The tap root systems of tree species access nutrients from deeper soil layers and return them to the surface through litterfall and roots, thereby enriching the nutrient pool in the upper soil layers (Abbasi Surki *et al*., 2021).

Agroforestry also serves as an appropriate technology for areas with fragile ecosystems and subsistence farming. Trees, with their access to deeper nutrient pools, absorb nutrients from the lower root zone and return them to the subsurface through litterfall and root turnover, which helps accumulate nutrients and improve soil physical properties (Singh and Rathod, 2006) and nutrient-use efficiency in the system (Buresh *et al*., 2004).

The growing human population is driving an unprecedented demand for food and natural resources. Achieving the required levels of food production cannot be accomplished by the agricultural sector alone. A viable solution to this challenge involves a combination of technological advancements and the integration of other natural ecosystems (Licker *et al*., 2010).

In agroforestry systems (AFS), the presence of both trees and crops in the same area facilitates nutrient return to the soil through leaf litter, making nutrient cycling studies essential for understanding nutrient balance and the removal of nutrients from the plantation area (Bhardwaj *et al*., 2001). Additionally, the increase in clay and silt content and the decrease in sand content, along with a notable rise in cation exchange capacity, have been observed in tree plantations (Balamurugan *et al*., 2000).

Eucalyptus plantations have been shown to improve soil salinity and sodicity by reducing soil electrical conductivity (EC), pH, and sodium adsorption ratio (SAR) (Nasim *et al*., 2007). However, the effects of Eucalyptus cultivation on soil, particularly related to fertility, are not well-defined. Parwi *et al.* (2022) investigated the effects of agroforestry systems on soil microbial biomass in Indonesia, comparing pine-based agroforestry, sengon-based agroforestry, and monoculture. Soil samples were analyzed at depths of 0–30 cm and 30–60 cm. The findings indicated that sengon-based agroforestry supported significantly higher microbial biomass than both pine-based agroforestry and monoculture, highlighting its potential benefits for soil health. Therefore, understanding the impact of Eucalyptus on soil nutrient reserves and organic matter is crucial for developing sustainable agroforestry practices.

Among agroforestry tree species, Eucalyptus is of significant importance due to its rapid and uniform growth, self-pruning ability, coppicing capacity, and smaller canopy compared to most other tree species. Due to its fast growth and potential, Eucalyptus provides a livelihood for many rural and urban populations in the country. This species has been widely used to meet the demand for pulpwood and industrial wood, and the use of Eucalyptus clones has increased the productivity and profitability of plantations in several states (Lal, 2005). Its integration into various farming systems has resulted in higher economic profitability compared to traditional crop production.

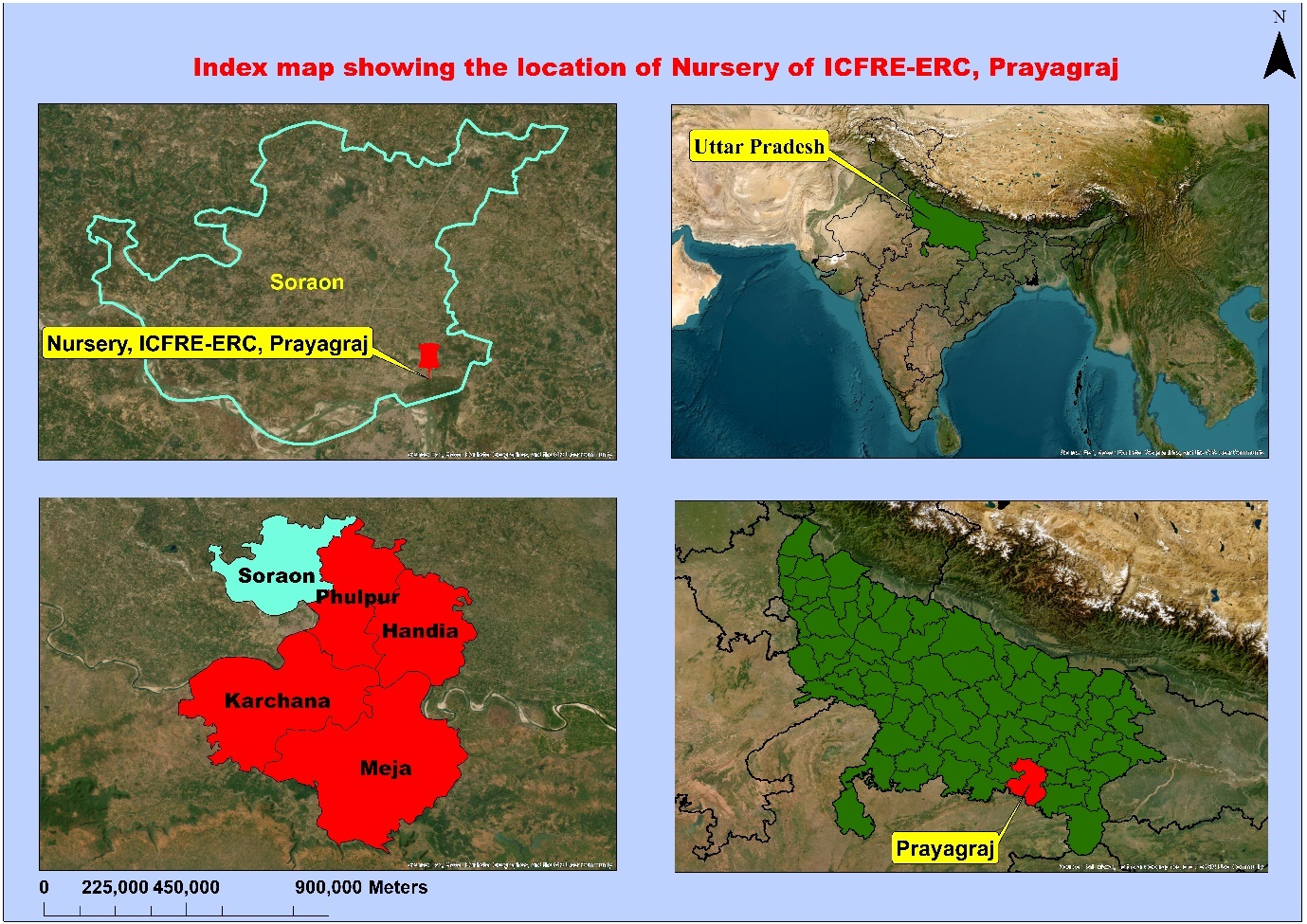
Eucalyptus trees can be planted within fields or along field edges. Tree species in AFS contribute large amounts of organic matter through litterfall and root residues, which, upon decomposition, release significant amounts of macro- and micronutrients into the soil and improve its physicochemical properties (Singh *et al*., 2016; Kumar *et al*., 2019). Growing interest in Eucalyptus farm forestry has led to the conversion of croplands into Eucalyptus woodlots (Dereje *et al*., 2012). Eucalyptus plantations improve soil nutrients (N, P, K, and organic matter) compared to natural soils (Jha *et al*., 1996).

In AFS, tree species not only release organically bound nutrients through the decomposition of organic matter, but the decomposition products also help solubilize nutrients present in soil minerals (Kaur *et al*., 2020). The presence of high organic matter and clay content releases exchangeable bases and salts through microbial decomposition, influencing soil chemical properties such as cation exchange capacity (CEC) and EC (Tashi *et al*., 2016; Kassa *et al*., 2017). These systems increase soil organic matter, improve soil porosity, reduce bulk density, and enhance soil structure, which ultimately improves the soil’s water-holding capacity (Sharma *et al*., 2015; Meena *et al*., 2018). With this background, the present study aims to evaluate the effects of Eucalyptus trees under seven different land use systems on various soil characteristics.

**MATERIAL AND METHODS**

**Study area**

The present investigation was carried out at the Padila Nursery, Indian Council of Forestry Research and Education, Eco-Rehabilitation Centre, Prayagraj, U.P. Geographically, Padila Nursery is situated at 25⁰ 32’ 39’’N latitude, 81⁰ 53’27’’E longitude and at altitude of 122 metres above the mean sea level. Figure 1 shows the location of the study area. It is located about 11 kilometres away in North East from Prayagraj city.



**Fig. 1 Index map of the study area**

Prayagraj experiences a humid subtropical climate (Köppen: Cwa), characteristic of cities in the North Indian plains. The city's annual mean temperature is 26.1 °C (79.0 °F), with monthly averages ranging from 18 °C to 29 °C (64–84 °F). It has three distinct seasons: a hot, dry summer; a cool, dry winter; and a hot, humid monsoon. Summer extends from March to September, with temperatures soaring to 48 °C (118 °F) in the arid pre-monsoon months (March–May) and up to 40 °C (104 °F) during the monsoon (June–September), when oppressive humidity dominates. The monsoon season, from June to August, brings heavy rainfall, while high humidity lingers into September. Winters, spanning December to February, are mild, with daytime temperatures averaging around 22 °C (72 °F) and nighttime lows around 9 °C (48 °F), rarely approaching freezing. About 88 percent of the annual rainfall is received during the monsoon season July and August being the months of maximum rainfall. The annual rainfall in the district is 978 mm.

**Experimental design**

The five years old plantation of Eucalyptus (*Eucalyptus camaldulensis*) with 3.0 x 2.0 m spacing was used for intercropping study. Two medicinal plants *viz*. Tulsi (*Ocimum sanctum* L.) variety CIM-Ayu and Mint (*Mentha arvensis* L.) variety CIM-Kranti were selected for the present study. The experiment was conducted during kharif season, 2022 and 2023. Four replications of seven land use systems (treatments) were selected. These systems were T1:Eucalyptus+Mentha+Tulsi, T2:Eucalyptus+Mentha, T3:Eucalyptus+Tulsi, T4:Eucalyptus Sole, T5:Mentha+ Tulsi Sole, T6:Mentha Sole and T7:Tulsi sole. The experiment was conducted in randomised block design. The medicinal plants were transplanted in the experimental plot in the spacing of 50.0 x 50.0 cm during april and were harvested in september for the two consecutive years.

**Soil sampling**

Soil sampling was conducted at six randomly selected locations within each of the chosen sites. For each replication of all treatments, soil samples were collected from two distinct depths (0-15 cm and 15-30 cm) using an auger. These depths were chosen to assess the impact of litterfall and tree roots on both surface and deeper soil layers. The primary soil samples collected were thoroughly mixed to create composite samples. These composite samples were then air-dried, ground, and sieved through a 2 mm mesh before being used for the analysis of various soil characteristics.

**Soil analysis**

The soil pH were determined in soil: distilled water suspension (1:2). The available N in the soil was determined by alkaline permanganate method (Subbiah and Asija, 1956), Soil organic carbon was determined by Walkley and Black (1934) rapid titration method. available P by sodium bicarbonate method (Olsen *et al*., 1954) and available K by neutral normal ammonium acetate method (Jackson, 1973). The data obtained during the course of this investigation, were analysed by using standard statistical procedure (Panse and Sukhatme, 1989).

**RESULTS AND DISCUSSION**

The influence of different tree based AFS (T1, T2, T3, T4) in comparison to sole crops (T5, T6 and T7) was observed on soil chemical properties, namely soil pH and organic carbon. The depth-wise distribution of available macronutrients N, P and K was also recorded.

**Soil pH**

The data analysis presented in Table no. 1 revealed a statistically significant difference in soil pH between sole crops and Eucalyptus-based agroforestry systems, although the treatments were not significant at the 0.05% level of significance. At the 0-15 cm depth, soil pH ranged from 7.24 to 7.63. In the first year (2022) of the study, the highest soil pH (7.63) was observed under T5: Mentha + Tulsi Sole, while the lowest (7.28) was recorded under T3: Eucalyptus + Tulsi, which was statistically similar to T2: Eucalyptus + Mentha (7.32). In the second year (2023), the highest soil pH (7.60) was recorded under T5: Mentha + Tulsi Sole, while the lowest (7.24) was observed under T3: Eucalyptus + Tulsi, which was statistically comparable to T2: Eucalyptus + Mentha (7.28). The trend followed was T5 > T6 > T7 > T4 > T1 > T2 > T3 at the 0-15 cm depth.

At the 15-30 cm depth, soil pH ranged from 7.32 to 7.68. In the first year (2022), the highest pH (7.68) was recorded under T5: Mentha + Tulsi Sole, while the lowest (7.34) was observed under T3: Eucalyptus + Tulsi, which was statistically similar to T2: Eucalyptus + Mentha (7.38). In the second year (2023), the highest pH (7.66) was observed under T5: Mentha + Tulsi Sole, while the lowest pH (7.32) was recorded under T3: Eucalyptus + Tulsi, which was statistically comparable to T2: Eucalyptus + Mentha (7.36). Similar trends were observed at both soil depths, with T5 > T6 > T7 > T4 > T1 > T2 > T3.

The results demonstrated that soil pH increased with depth, and pH was higher in the open system compared to the agroforestry systems. The lower pH in agroforestry systems compared to sole cropping and fallow land could be due to increased H+ ion concentration from litterfall decomposition, depletion of basic cations, and higher CO2 levels from root respiration, which all contribute to a reduction in soil pH in areas with trees (Uthappa *et al*., 2015). Kaur *et al*. (2020) also reported that soil pH was highest in fallow land and lowest in sites with 30-year-old poplar plantations. Nasim *et al*. (2007) found that Eucalyptus plantations can reduce soil salinity and sodicity by lowering soil electrical conductivity (EC), pH, and sodium adsorption ratio (SAR). Sharma *et al.* (2022) conducted study where poplar and eucalyptus were intercropped with different wheat varieties. The results showed higher levels of pH under open farming system. Ramesh *et al*. (2023) observed that after harvesting intercrops, soil pH slightly decreased compared to initial levels, with the highest pH found in tree-only treatments, followed by sorghum and maize treatments.

**Soil organic carbon**

Table no. 2 reveals a significant difference in organic carbon content between open and agroforestry systems at both 0-15 cm and 15-30 cm soil depths for all treatments, with all treatments being statistically significant at the 5% level of significance. At the 0-15 cm depth, soil organic carbon content ranged from 0.68 to 0.90 gm/kg. In 2022, the highest organic carbon content was recorded in T3: Eucalyptus + Tulsi (0.86 gm/kg), followed by T2: Eucalyptus + Mentha (0.83 gm/kg), T1: Eucalyptus + Mentha + Tulsi (0.79 gm/kg), and T4: Eucalyptus Sole (0.76 gm/kg), while the lowest organic carbon content was found in T5: Mentha + Tulsi Sole (0.68 gm/kg). In 2023, the highest organic carbon content was recorded again in T3: Eucalyptus + Tulsi (0.90 gm/kg), followed by T2: Eucalyptus + Mentha (0.84 gm/kg), T1: Eucalyptus + Mentha + Tulsi (0.81 gm/kg), and T4: Eucalyptus Sole (0.79 gm/kg), with the lowest content again in T5: Mentha + Tulsi Sole (0.71 gm/kg). The trend observed was T3 > T2 > T1 > T4 > T7 > T6 > T5 at the 0-15 cm depth.

At the 15-30 cm depth, soil organic carbon content ranged from 0.47 to 0.55 gm/kg. In 2022, the highest organic carbon content was recorded in T3: Eucalyptus + Tulsi (0.54 gm/kg), followed by T2: Eucalyptus + Mentha (0.52 gm/kg), T1: Eucalyptus + Mentha + Tulsi (0.51 gm/kg), and T4: Eucalyptus Sole (0.50 gm/kg), with the lowest content in T5: Mentha + Tulsi Sole (0.47 gm/kg). In 2023, the highest organic carbon content was recorded in T3: Eucalyptus + Tulsi (0.55 gm/kg), followed by T2: Eucalyptus + Mentha (0.54 gm/kg), T1: Eucalyptus + Mentha + Tulsi (0.53 gm/kg), and T4: Eucalyptus Sole (0.50 gm/kg), with the lowest content in T5: Mentha + Tulsi Sole (0.48 gm/kg). The trend followed was T3 > T2 > T1 > T4 > T7 > T6 > T5 at the 15-30 cm depth. Among the two medicinal plants, Tulsi in agroforestry systems recorded the highest soil organic carbon content compared to open systems. Agroforestry systems proved to be more effective in increasing organic carbon content across all crop plots under Eucalyptus-based agroforestry systems. In general, organic carbon levels were higher in tree-crop combinations than in sole cropping systems. This higher organic carbon content under tree-crop combinations can be attributed to the accumulation of organic matter, such as leaf litter, fine root biomass, and root exudates, along with reduced oxidation of organic matter under the tree canopy. The upper soil layer (0-15 cm) showed particularly high organic carbon levels, likely due to these factors. This finding is in line with Gupta *et al*. (2009), who observed that trees, with their lignified cells, help stabilize organic carbon in soil. The results of the present study are also consistent with the findings of Aweto and Moleele (2005), Tian *et al*. (2013), Singh and Jhariya (2014), Kumar *et al*. (2018), and Kumar *et al*. (2019).

**Soil macronutrients (available N, P and K)**

***Available Nitrogen***

The available nitrogen data recorded during both years of the study (2022 and 2023) at 0-15 cm and 15-30 cm soil depths is presented below (Table no. 3). In 2022, the maximum available nitrogen at 0-15 cm depth was observed in T3: Eucalyptus + Tulsi (238.54 kg/ha), which was significantly similar to T2: Eucalyptus + Mentha (232.55 kg/ha), T1: Eucalyptus + Mentha + Tulsi (227.83 kg/ha), and T4: Eucalyptus Sole (225.67 kg/ha), while the lowest available nitrogen was recorded in T5: Mentha + Tulsi Sole (183.24 kg/ha), which was statistically similar to T7: Tulsi Sole (191.37 kg/ha) and T6: Mentha Sole (188.61 kg/ha). In 2023, a similar trend was observed at 0-15 cm depth, with the highest available nitrogen content in T3: Eucalyptus + Tulsi (241.91 kg/ha), followed by T2: Eucalyptus + Mentha (235.35 kg/ha), T1: Eucalyptus + Mentha + Tulsi (230.17 kg/ha), and T4: Eucalyptus Sole (227.38 kg/ha), while the lowest nitrogen content was recorded in T5: Mentha + Tulsi Sole (185.47 kg/ha), which was statistically similar to T7: Tulsi Sole (195.31 kg/ha) and T6: Mentha Sole (191.04 kg/ha).

At the 15-30 cm depth in 2022, available nitrogen ranged from 170 kg/ha to 228 kg/ha. The maximum value was observed in T3: Eucalyptus + Tulsi (226.09 kg/ha), which was statistically similar to T2: Eucalyptus + Mentha (220.91 kg/ha), T1: Eucalyptus + Mentha + Tulsi (213.33 kg/ha), and T4: Eucalyptus Sole (211.58 kg/ha), while the lowest available nitrogen was recorded in T5: Mentha + Tulsi Sole (170.54 kg/ha), which was statistically similar to T7: Tulsi Sole (179.43 kg/ha) and T6: Mentha Sole (173.92 kg/ha). In 2023, the maximum nitrogen content was again found in T3: Eucalyptus + Tulsi (228.05 kg/ha), which was statistically similar to T2: Eucalyptus + Mentha (221.75 kg/ha), T1: Eucalyptus + Mentha + Tulsi (214.80 kg/ha), and T4: Eucalyptus Sole (211.82 kg/ha), while the lowest value was recorded in T5: Mentha + Tulsi Sole (171.08 kg/ha), statistically similar to T7: Tulsi Sole (181.61 kg/ha) and T6: Mentha Sole (174.49 kg/ha). Singh *et al*. (2010) and Devi *et al*. (2020) reported higher available nitrogen content in the plough layer compared to sub-surface layers in agroforestry systems. Singh *et al.* (2022) conducted a study to compare the depth-wise distribution of soil physico-chemical properties and nutrient status under several land-use systems, and found that poplar-based rotation (T1) had the highest available nitrogen in all soil depths.

***Available Phosphorous***

The data for available phosphorus (Table no. 4) at 0-15 cm depth in 2022 showed the highest content in T3: Eucalyptus + Tulsi (28.65 kg/ha), which was statistically similar to T2: Eucalyptus + Mentha (26.07 kg/ha), followed by T1: Eucalyptus + Mentha + Tulsi (23.44 kg/ha) and T4: Eucalyptus Sole (22.05 kg/ha). The lowest phosphorus content was recorded in T5: Mentha + Tulsi Sole (16.98 kg/ha), which was statistically similar to T7: Tulsi Sole (20.51 kg/ha) and T6: Mentha Sole (18.63 kg/ha). In 2023, the highest phosphorus content was recorded in T3: Eucalyptus + Tulsi (29.05 kg/ha), followed by T2: Eucalyptus + Mentha (27.13 kg/ha), T1: Eucalyptus + Mentha + Tulsi (23.93 kg/ha), and T4: Eucalyptus Sole (22.15 kg/ha), with the lowest phosphorus content in T5: Mentha + Tulsi Sole (17.33 kg/ha), statistically similar to T7: Tulsi Sole (21.14 kg/ha) and T6: Mentha Sole (19.03 kg/ha).

At 15-30 cm depth, the available phosphorus content ranged from 13.49 kg/ha to 25.86 kg/ha. In 2022, the highest value was recorded in T3: Eucalyptus + Tulsi (24.83 kg/ha), followed by T2: Eucalyptus + Mentha (22.57 kg/ha), T1: Eucalyptus + Mentha + Tulsi (19.63 kg/ha), and T4: Eucalyptus Sole (18.28 kg/ha), with the lowest content recorded in T5: Mentha + Tulsi Sole (13.49 kg/ha), statistically similar to T6: Mentha Sole (15.49 kg/ha). In 2023, the highest phosphorus content was observed in T3: Eucalyptus + Tulsi (25.86 kg/ha), followed by T2: Eucalyptus + Mentha (23.43 kg/ha), T1: Eucalyptus + Mentha + Tulsi (19.88 kg/ha), and T4: Eucalyptus Sole (19.76 kg/ha), while the lowest content was recorded in T5: Mentha + Tulsi Sole (13.83 kg/ha), statistically similar to T6: Mentha Sole (16.36 kg/ha). The data followed the trend: T3 > T2 > T1 > T4 > T7 > T6 > T5. The increased phosphorus content in tree-based agroforestry systems (AFS) is attributed to the release of organic acids, reduced pH, and less phosphorus fixation on exchange sites (Zhang *et al*., 2019). Yang *et al*. (2018) showed that available phosphorus and potassium were significantly higher in afforestation sites compared to degraded croplands due to the addition of exogenous inputs from litter and rhizodeposition.

***Available Potassium***

Regarding available potassium (Table no. 5). at 0-15 cm depth in 2022, the values ranged from 102.22 kg/ha to 140.08 kg/ha. The highest potassium content was recorded in T3: Eucalyptus + Tulsi (130.97 kg/ha), which was statistically similar to T2: Eucalyptus + Mentha (128.91 kg/ha), followed by T1: Eucalyptus + Mentha + Tulsi (117.90 kg/ha) and T4: Eucalyptus Sole (115.95 kg/ha), while the lowest available potassium content was observed in T5: Mentha + Tulsi Sole (102.22 kg/ha), statistically similar to T6: Mentha Sole (107.61 kg/ha). In 2023, the maximum potassium content was again observed in T3: Eucalyptus + Tulsi (140.08 kg/ha), followed by T2: Eucalyptus + Mentha (133.40 kg/ha), T1: Eucalyptus + Mentha + Tulsi (125.45 kg/ha), and T4: Eucalyptus Sole (123.73 kg/ha), with the minimum content recorded in T5: Mentha + Tulsi Sole (110.70 kg/ha), statistically similar to T6: Mentha Sole (116.25 kg/ha).

At 15-30 cm depth in 2022, available potassium ranged from 96.76 kg/ha to 123.89 kg/ha. The highest content was recorded in T3: Eucalyptus + Tulsi (123.89 kg/ha), which was statistically similar to T2: Eucalyptus + Mentha (117.29 kg/ha), followed by T1: Eucalyptus + Mentha + Tulsi (111.76 kg/ha) and T4: Eucalyptus Sole (110.86 kg/ha). The lowest value was observed in T5: Mentha + Tulsi Sole (96.76 kg/ha), statistically similar to T6: Mentha Sole (116.25 kg/ha) and T7: Tulsi Sole (103.25 kg/ha). In 2023, the highest available potassium content was recorded in T3: Eucalyptus + Tulsi (127.15 kg/ha), followed by T2: Eucalyptus + Mentha (120.21 kg/ha), T1: Eucalyptus + Mentha + Tulsi (113.71 kg/ha), and T4: Eucalyptus Sole (113.31 kg/ha), with the lowest value in T5: Mentha + Tulsi Sole (98.59 kg/ha), statistically similar to T6: Mentha Sole (104.01 kg/ha) and T7: Tulsi Sole (106.15 kg/ha). The data followed the trend: T3 > T2 > T1 > T4 > T7 > T6 > T5. Ramesh *et al*. (2013) observed a 76% increase in soil available potassium in multipurpose tree species compared to controls.

**CONCLUSION**

The chemical properties and nutrient status of the soil were enhanced under tree-based agroforestry systems (AFS) compared to sole cropping. Specifically, available macronutrients (N, P, and K) and organic carbon were higher in tree-based AFS, while pH levels were higher in sole cropping systems. As a result, the need for fertilizer application to intercrops may be reduced due to the improvement in soil properties and nutrient content from the long-term adoption of tree-based AFS. However, further research is needed to determine the duration of the trees' impact on soil quality after the harvesting of tree species. Additionally, future studies should focus on evaluating the different nutrient fractions in soil under tree-based AFS and their relationship with crop and tree growth.

**Table 1** Soil pH content at the depth of 0-15cm and 15-30 cm in the agroforestry system in sole and combinations

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatments name** | **0-15 cm** | | | | **15-30 cm** | | | |
| **2022** | **S.E.** | **2023** | **S.E.** | **2022** | **S.E.** | **2023** | **S.E.** |
| T1:Eucalyptus+Mentha+Tulsi | 7.38cd | 0.013 | 7.36c | 0.017 | 7.47d | 0.013 | 7.44c | 0.013 |
| T2:Eucalyptus+Mentha | 7.32de | 0.013 | 7.28d | 0.016 | 7.38e | 0.011 | 7.36d | 0.012 |
| T3:Eucalyptus+Tulsi | 7.28e | 0.043 | 7.24d | 0.044 | 7.34e | 0.042 | 7.32d | 0.046 |
| T4:Eucalyptus Sole | 7.43c | 0.026 | 7.37c | 0.036 | 7.51cd | 0.013 | 7.48c | 0.011 |
| T5:Mentha+ Tulsi Sole | 7.63a | 0.010 | 7.60a | 0.014 | 7.68a | 0.021 | 7.66a | 0.023 |
| T6:Mentha Sole | 7.54b | 0.019 | 7.49b | 0.020 | 7.60b | 0.017 | 7.58b | 0.017 |
| T7:Tulsi sole | 7.51b | 0.014 | 7.46b | 0.014 | 7.57bc | 0.015 | 7.55b | 0.016 |
| **Mean Value** | 7.44 | - | 7.40 | - | 7.51 | - | 7.48 | **-** |
| **F-Calculated** | 0.32 | - | 0.41 | - | 0.346 | - | 0.415 | **-** |
| **p-value** | 0.251 | - | 0.347 | - | 0.214 | - | 0.172 | **-** |
| **Initial soil pH** | System – 7.45  Open – 7.64 | | | | System – 7.53  Open – 7.71 | | | |

**Table 2** Organic carbon content (gm/Kg) at the depth of 0-15cm and 15-30 cm in the agroforestry system in sole and combinations

| **Treatments name** | **0-15 cm** | | | | **15-30 cm** | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **2022** | **S.E.** | **2023** | **S.E.** | **2022** | **S.E.** | **2023** | **S.E.** |
| T1:Eucalyptus+Mentha+Tulsi | 0.79c | 0.009 | 0.81c | 0.015 | 0.51a | 0.006 | 0.53bc | 0.006 |
| T2:Eucalyptus+Mentha | 0.83b | 0.011 | 0.84b | 0.016 | 0.52a | 0.010 | 0.54b | 0.010 |
| T3:Eucalyptus+Tulsi | 0.86a | 0.007 | 0.90a | 0.014 | 0.54a | 0.018 | 0.55a | 0.020 |
| T4:Eucalyptus Sole | 0.76d | 0.012 | 0.79d | 0.004 | 0.50a | 0.011 | 0.52c | 0.013 |
| T5:Mentha+ Tulsi Sole | 0.68g | 0.010 | 0.71g | 0.010 | 0.47a | 0.004 | 0.48d | 0.002 |
| T6:Mentha Sole | 0.71f | 0.010 | 0.73f | 0.007 | 0.48a | 0.009 | 0.49d | 0.009 |
| T7:Tulsi sole | 0.73e | 0.016 | 0.76e | 0.022 | 0.50a | 0.006 | 0.51c | 0.006 |
| **Mean Value** | 0.77 | - | 0.79 | - | 0.51 | - | 0.52 | - |
| **F-Calculated** | 41.45 | - | 41.20 | - | 7.84 | - | 7.67 | - |
| **p-value** | 0.00 | - | 0.00 | - | 0.00 | - | 0.003 | - |
| **Initial Organic carbon (gm/Kg)** | System – 0.75  Open – 0.71 | | | | System – 0.50  Open – 0.47 | | | |

**Table 3** Available nitrogen (Kg/ha) at the depth of 0-15cm and 15-30 cm in the agroforestry system in sole and combinations

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatments name** | **0-15 cm** | | | | **15-30 cm** | | | |
| **2022** | **S.E.** | **2023** | **S.E.** | **2022** | **S.E.** | **2023** | **S.E.** |
| T1:Eucalyptus+Mentha+Tulsi | 227.83a | 3.189 | 230.17a | 4.180 | 213.33a | 3.626 | 214.98a | 3.655 |
| T2:Eucalyptus+Mentha | 232.55a | 2.885 | 235.35a | 5.932 | 220.91a | 2.809 | 221.75a | 3.145 |
| T3:Eucalyptus+Tulsi | 238.54a | 4.269 | 241.91a | 3.145 | 226.09a | 3.833 | 228.05a | 4.388 |
| T4:Eucalyptus Sole | 225.67a | 1.627 | 227.38a | 2.402 | 211.58a | 2.385 | 211.82a | 1.092 |
| T5:Mentha+ Tulsi Sole | 183.24b | 3.283 | 185.47b | 3.352 | 170.54b | 3.562 | 171.08b | 4.747 |
| T6:Mentha Sole | 188.61b | 4.347 | 191.04b | 6.404 | 173.92b | 4.220 | 174.49b | 5.791 |
| T7:Tulsi sole | 191.37b | 7.524 | 195.31b | 8.033 | 179.43b | 7.934 | 181.61b | 8.039 |
| **Mean Value** | 212.55 | - | 215.23 | - | 199.40 | - | 200.54 | - |
| **F-Calculated** | 28.12 | - | 18.63 | - | 26.22 | - | 22.13 | - |
| **p-value** | 0.00 | - | 0.00 | - | 0.00 | - | 0.00 | - |
| **Initial nitrogen (Kg/ha)** | System - 223.11  Open – 181.03 | | | | System – 208.16  Open – 168.10 | | | |

**Table 4** Available phosphorous (Kg/ha) at the depth of 0-15cm and 15-30 cm in the agroforestry system in sole and combinations

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatments name** | **0-15 cm** | | | | **15-30 cm** | | | | |
| **2022** | **S.E.** | **2023** | **S.E.** | **2022** | **S.E.** | **2023** | **S.E.** |
| T1:Eucalyptus+Mentha+Tulsi | 23.44bc | 0.878 | 23.93b | 1.357 | 19.63b | 0.475 | 19.88b | 0.412 |
| T2:Eucalyptus+Mentha | 26.07ab | 2.516 | 27.13a | 2.078 | 22.57a | 2.218 | 23.43a | 2.357 |
| T3:Eucalyptus+Tulsi | 28.65a | 1.099 | 29.05a | 0.638 | 24.83a | 1.133 | 25.86a | 1.153 |
| T4:Eucalyptus Sole | 22.05cd | 0.583 | 22.15b | 1.393 | 18.28bc | 0.864 | 19.76b | 0.349 |
| T5:Mentha+ Tulsi Sole | 16.98e | 0.420 | 17.33c | 1.138 | 13.49d | 0.474 | 13.83d | 0.427 |
| T6:Mentha Sole | 18.63de | 0.318 | 19.03bc | 1.155 | 15.49cd | 0.352 | 16.36cd | 0.452 |
| T7:Tulsi sole | 20.51cde | 0.399 | 21.14bc | 1.210 | 17.35bc | 0.650 | 18.04bc | 0.688 |
| **Mean Value** | 22.34 | - | 22.69 | - | 18.80 | - | 19.60 | - |
| **F-Calculated** | 13.81 | - | 11.75 | - | 19.03 | - | 19.11 | - |
| **p-value** | 0.001 | - | 0.002 | - | 0.00 | - | 0.00 | - |
| **Initial Phosphorous (Kg/ha)** | System – 20.41  Open – 16.11 | | | | System – 17.23  Open – 12.46 | | | |

**Table 5** Available potassium (Kg/ha) at the depth of 0-15cm and 15-30 cm in the agroforestry system in sole and combinations

| **Treatments name** | **0-15 cm** | | | | **15-30 cm** | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **2022** | **S.E.** | **2023** | **S.E.** | **2022** | **S.E.** | **2023** | **S.E.** |
| T1:Eucalyptus+Mentha+Tulsi | 117.90b | 1.095 | 125.45c | 3.569 | 111.76bc | 1.449 | 113.71bc | 1.573 |
| T2:Eucalyptus+Mentha | 128.91a | 0.862 | 133.40b | 4.732 | 117.29ab | 2.904 | 120.21ab | 2.707 |
| T3:Eucalyptus+Tulsi | 130.97a | 2.579 | 140.08a | 1.457 | 123.89a | 3.264 | 127.15a | 3.682 |
| T4:Eucalyptus Sole | 115.95bc | 1.724 | 123.73c | 3.562 | 110.86bcd | 1.510 | 113.31bc | 1.094 |
| T5:Mentha+ Tulsi Sole | 102.22e | 2.088 | 110.70e | 4.307 | 96.76e | 2.512 | 98.59d | 2.564 |
| T6:Mentha Sole | 107.61de | 3.149 | 116.25de | 2.593 | 101.21de | 3.307 | 104.01cd | 2.937 |
| T7:Tulsi sole | 110.64cd | 0.799 | 118.21d | 3.714 | 103.25cde | 4.201 | 106.15cd | 4.417 |
| **Mean Value** | 116.31 | - | 123.97 | - | 109.29 | - | 111.88 | - |
| **F-Calculated** | 31.87 | - | 35.23 | - | 9.44 | - | 10.36 | - |
| **p-value** | 0.00 | - | 0.00 | - | 0.001 | - | 0.001 | - |
| **Initial Potassium (Kg/ha)** | System – 114.36  Open – 100.11 | | | | System – 108.16  Open – 93.31 | | | |

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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