***Original Research Article***

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

**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. A high soil pH was found in an open farming system and lower pH in an agroforestry system. 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 (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. 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. It is located about 11 kilometres away in North East from Prayagraj city. The climate of Prayagraj district where the Padila Nursery is located, is typical humid subtropical as experienced by the whole north-central India. The area experiences different seasons with climate varying from extreme hot to extreme cold. It has three seasons: hot dry summer, warm humid monsoon and cool dry winter. The monsoon season starts from mid of June to September. 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). 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*)**

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. 3,4 and 5). 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). The data for available phosphorus 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. Regarding available potassium 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. 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. 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. 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 | | | |

**REFERENCES**

Abbasi Surki, A., Nazari, M., Fallah, S., and Iranipour, R. (2021). Improvement of the soil properties, nutrients, and carbon stocks in different cereal–legume agroforestry systems. *International Journal of Environmental Science and Technology*, *18*, 123-130.

Aweto, A. O., and Moleele, N. M. (2005). Impact of *Eucalyptus camaldulensis* plantation on an alluvial soil in south eastern Botswana. *International journal of environmental studies*, 62(2), 163-170. <https://doi.org/10.1080/0020723042000275141>

Balamurugan, J., Kumar, K., Swamy, A., and Rajarajan, A. (2000). Effects of *Eucalyptus citriodora* on the physical and chemical properties of soils. *Journal of the Indian Society of soil science*, *48*(3), 491-495.

Bhardwaj, S. D., Pankaj Panwar, P. P., and Sachil Gautam, S. G. (2001). Biomass production potential and nutrient dynamics of *Populus deltoides* under high density plantations. *Indian Forester*, 127: 144-153.

Buresh, R. J., Rowe, E. C., Livesley, S. J., Cadisch, G., and Mafongoya, P. (2004). Opportunities for capture of deep soil nutrients. In: van Noordwijk M, Cadisch G and Ong CK,editors. Belowground interactions in tropical agroecosystems: concepts and models with multiple plant components. Wallingford: CABI International,109-125.

Dereje, J., Mulugeta, L., and Kassa, H. (2012) Expansion of eucalyptus farm forestry and its determinants in Arsi Negelle District, south central Ethiopia. *Small Scale Forestry*. 11(3):389-405.

Devi, S., Bhardwaj, K. K., Dahiya, G., Sharma, M. K., Verma, A. K., and Louhar, G. (2020). Effect of agri-silvi-horticultural system on soil chemical properties and available nutrients at different depths in Haryana. *Range Management and Agroforestry*, *41*(2), 267-275.

Gupta, N., Kukal, S. S., Bawa, S. S., and Dhaliwal, G. S. (2009). Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. In *Advances in Agroforestry,* 76: 27-35. Springer, Dordrecht.

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

Jha, M. N., Dimri, B. M., and Gupta, M. K. (1996). Soil nutrient changes under different ages of Eucalyptus monocultures.*Indian Forester*. 122:55-60.

Kassa, H., Dondeyne, S., Poesen, J., Frankl, A., and Nyssen, J. (2017). Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. *Agriculture, Ecosystems and Environment*, *247*, 273-282.

Kaur, R., Singh, B., and Dhaliwal, S. S. (2020). Dynamics of soil cationic micronutrients in a chronosequence of poplar (*Populus deltoides* Bartr.)-based agroforestry system in India. *Journal of Soil Science and Plant Nutrition*, *20*, 2025-2041.

Kumar, A., Das, D. K., and Singh, S. K. (2019). Variation in key soil properties after eleven years of poplar plantation in calciorthents of Bihar. *Range Management and Agroforestry*, *40*(2), 269-275.

Kumar, P., Mishra, A. K., Chaudhari, S. K., Basak, N., Rai, P., Singh, K., ... and Sharma, D. K. (2018). Carbon pools and nutrient dynamics under Eucalyptus-based agroforestry system in semi-arid region of north-west India. *Journal of the Indian Society of Soil Science*, 66(2), 188-199.

Kumar, T., Kumari, B., Arya, S., and Kaushik, P. (2019). Effect of different spacings of Eucalyptus based agroforestry systems soil nutrient status and chemical properties in semi-arid ecosystem of India. *Journal of Pharmacognosy and Phytochemistry*, 8(3), 18-23.

Lal, P. (2004). Integrated development of farm-forestry plantations and wood based industries. *Indian Forester*, *130*(1), 71-78.

Licker, R., Johnston, M., Foley, J. A., Barford, C., Kucharik, C. J., Monfreda, C., and Ramankutty, N. (2010). Mind the gap: how do climate and agricultural management explain the ‘yield gap’of croplands around the world?. *Global ecology and biogeography*, *19*(6), 769-782.

Meena, V. S., Mondal, T., Pandey, B. M., Mukherjee, A., Yadav, R. P., Choudhary, M., ... and Pattanayak, A. (2018). Land use changes: Strategies to improve soil carbon and nitrogen storage pattern in the mid-Himalaya ecosystem, India. *Geoderma*, *321*, 69-78.

Nasim, M., Qureshi, R. H., Saqib, M., Aziz, T., Nawaz, S., Akhtar, J., and Anwar-ul-Haq, M. (2007). Properties of salt affected soil under *Eucalyptus camaldulensis* plantation in field conditions. *Pakistan Journal of Agricultural Sciience*, *44*(3), 401-414.

Olsen, S. R. (1954). Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. *US Department of Agriculture*.

Panse, V. G., and Sukhatme, P. V. (1954). Statistical methods for agricultural workers., 4th Edition, ICAR, New Delhi.

Ramesh, K. R., Deshmukh, H. K., Sivakumar, K., Guleria, V., Umedsinh, R. D., Krishnakumar, N., Thangamalar, A., Suganya, K., Kiruba, M., Selvan, T., Balasubramanian, P., Ushamalini, C., Thiyagarajan, G., Vincent, S., Rajeswari, P., Bavish, S., Riaz, A., and Senthil, K. (2023). Influence of Eucalyptus Agroforestry on Crop Yields, Soil Properties, and System Economics in Southern Regions of India. Sustainability, 15(4), 3797. <https://doi.org/10.3390/su15043797>

Ramesh, T., Manjaiah, K. M., Tomar, J. M. S., and Ngachan, S. V. (2013). Effect of multipurpose tree species on soil fertility and CO2 efflux under hilly ecosystems of Northeast India. *Agroforestry systems*, *87*, 1377-1388.

Sharma, S., Singh, B., and Sikka, R. (2015). Soil organic carbon and nitrogen pools in a chronosequence of poplar (*Populus deltoides*) plantations in alluvial soils of Punjab, India. *Agroforestry systems*, *89*, 1049-1063.

Singh, B., Gill, R. I. S., and Gill, P. S. (2010). Soil fertility under various tree species and poplar-based agroforestry system. *Agricultural Research Journal*, *47*(3-4), 160-64.

Singh, B., Singh, P., and Gill, R. I. S. (2016). Seasonal variation in biomass and nitrogen content of fine roots of bead tree (*Melia azedarach*) under different nutrient levels in an agroforestry system. *Range Management and Agroforestry*, *37*(2), 192-200.

Singh, G. (2010). Rainfall dependent competition effected productivity of *V. radiata* in *Hardwickia binata* agroforestry in Indian Desert. *Indian Forester*, *136*, 301-315.

Singh, G., and Rathod, T. R. (2007). Growth, production and resource use in *Colophospermum mopane*-based agroforestry system in north-western India: (Wachstum, Produktion und Ressourcennutzung in einem auf Colophospermum mopane basierenden Agroforestry-System in Nordwest Indien). *Archives of Agronomy and soil science*, *53*(1), 75-88.

Singh, N. R., and Jhariya, M. K. (2014). Performance of soybean and soil properties under poplar based agroforestry system in tarai belt of Uttarakhand, India. *Ecology, Environment and Conservation*, 20:1569-1573.

Subbiah, B. V., and Asija, G. L. (1956). A rapid procedure for the estimation of available nitrogen in soils. *Current Science*. 25:259260.

Tashi, S., Singh, B., Keitel, C., and Adams, M. (2016). Soil carbon and nitrogen stocks in forests along an altitudinal gradient in the eastern Himalayas and a meta‐analysis of global data. *Global change biology*, *22*(6), 2255-2268.

Tian, Y., Cao, F., and Wang, G. (2013). Soil microbiological properties and enzyme activity in Ginkgo–tea agroforestry compared with monoculture. *Agroforestry systems*, *87*, 1201-1210.

Uthappa, A. R., Bana, O. P. S., Kumar, M., and Kanwal, M. (2015). Soil physico-bio-chemical properties as influenced by varying tree densities in poplar (*Populus deltoides* Bartr. ex Marsh.) based agroforestry system. *Indian Journal of Agroforestry*, *17*(1), 81-90.

Walkley, A., and Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science*, *37*(1), 29-38.

Yang, N., Ji, L., Yang, Y., and Yang, L. (2018). The influence of tree species on soil properties and microbial communities following afforestation of abandoned land in northeast China. *European Journal of Soil Biology*, *85*, 73-78.

Zhang, W., Liu, W., Xu, M., Deng, J., Han, X., Yang, G., ... and Ren, G. (2019). Response of forest growth to C: N: P stoichiometry in plants and soils during *Robinia pseudoacacia* afforestation on the Loess Plateau, China. *Geoderma*, *337*, 280-289.