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Agroforestry's impact on soil properties: Insights from a longitudinal study in a subtropical agro-climatic zone

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Abstract

A research study was conducted at the Forestry Research Farm of Jawaharlal Nehru Krishi Vishwa Vidyalaya in Jabalpur, India, during the Rabi seasons of 2021-22 and 2022-23. The primary focus of this investigation was a 14-year-old agroforestry model centered around *Pongamia pinnata*. The research site is located in a subtropical climate zone, characterized by black soil and gentle sloping topography within the Kymore Plateau and Satpura hill agro-climatic region. The study employed a rigorous experimental design, featuring a three-factor double split plot layout to assess the effects of various factors on soil properties. These factors included land use systems (open and agroforestry), sowing dates (D1-Nov. 12, D2-Nov. 27, and D3-Dec. 12), and two wheat varieties (V1-MP-3336 and V2-GW-322). The main objective was to evaluate the impact of these factors on critical soil characteristics. Soil samples were meticulously collected at depths of 15 cm and 30 cm and subsequently analyzed for key parameters, namely pH, electrical conductivity (EC), and organic carbon content. The results of this comprehensive analysis revealed several noteworthy findings. First and foremost, the agroforestry systems consistently exhibited a discernible trend towards lower pH values, elevated electrical conductivity, and significantly higher organic carbon content when compared to the open land use systems. These results underscore the considerable advantages of integrating tree-crop systems for carbon sequestration and the enhancement of soil fertility. This finding holds substantial implications for sustainable agricultural practices and improved land management in regions sharing similar agro-climatic characteristics. Furthermore, the impact of sowing dates on the measured soil properties appeared to be rather limited, with no statistically significant differences observed. This suggests that the timing of wheat sowing, within the range considered in the study, does not exert a significant influence on the selected soil properties. Finally, the two wheat varieties under examination, MP-3336 and GW-322, exhibited similar responses in terms of soil properties. This uniform response indicates that both varieties possess comparable adaptability to moderate soil salinity levels.

Keywords: Agroforestry, land use systems, soil properties, wheat, *Pongamia pinnata*

1. Introduction

Agroforestry is a sustainable and integrated land use system that has garnered considerable attention and acclaim for its profound influence on soil properties, specifically its effects on soil pH (acidity or alkalinity), electrical conductivity (EC) and soil organic carbon (SOC) content (Puri and Nair, 2004) [1]. This multifaceted approach to land management combines the practices of agriculture with the strategic inclusion of trees, effectively harnessing the benefits of both. The result is a remarkable transformation of soil characteristics, with implications that extend far beyond the immediate environment (Matocha *et al.* 2012) [2]. Agroforestry is an ancient practice, deeply rooted in indigenous traditions and various agricultural systems worldwide. However, it has gained renewed attention and significance in recent years, as global environmental concerns intensify, and sustainable land management practices become increasingly essential. The fundamental principle of agroforestry is the deliberate integration of trees and woody shrubs with crops and/or livestock on the same piece of land, fostering a harmonious coexistence that enriches the overall ecosystem (Hariram *et al.* 2023) [3]. This agroecological approach, often seen as a bridge between agriculture and forestry, promotes biodiversity, enhances soil fertility, mitigates climate change and sustains rural livelihoods (Tomich *et al.* 2011) [4]. One of the key areas where agroforestry demonstrates its prowess is in its influence on soil properties. Soil, as the foundation of terrestrial ecosystems, plays a critical role in supporting plant growth, regulating nutrient cycles and providing essential ecosystem services (Ben *et al.* 2011) [5]. Soil properties such as pH, EC and SOC content are pivotal indicators of soil health and functionality.

They directly affect plant growth, nutrient availability and overall ecosystem resilience. Agroforestry, with its ability to manipulate these properties, offers a promising solution to the challenges faced by modern agriculture and land management (Roy, 2016) [6].

Soil pH, a measure of soil acidity or alkalinity, is a crucial factor in determining the availability of essential nutrients for plant growth. Soil pH can significantly impact the solubility of nutrients in the soil solution and thus influence their accessibility to plants (Neina, 2019) [7]. Agroforestry systems often contribute to the amelioration of soil pH, as tree species within these systems can help regulate the pH levels of the surrounding soil. This alteration can enhance nutrient availability, thereby increasing crop productivity (Sileshi *et al.* 2020) [8]. In addition to nutrient availability, soil pH also influences soil microorganisms and the processes they mediate, ultimately affecting soil health and ecosystem functions. Electrical conductivity (EC) is another essential soil property influenced by agroforestry (Jia *et al.* 2022) [9]. It measures the ability of soil to conduct an electrical current and is a valuable indicator of soil salinity. Elevated EC levels can indicate soil salinization, a problem commonly associated with poor irrigation practices and inappropriate land management (Zaman *et al.* 2018) [10]. Agroforestry systems, by their very nature, can contribute to a reduction in soil salinity. Trees and their deep-rooting systems can help regulate water tables, reducing the risk of salt accumulation in the upper soil layers. Moreover, agroforestry practices often involve diversifying land use, which can help to balance water and nutrient cycles, further mitigating salinity issues (George *et al.* 2012) [11].

Soil Organic Carbon (SOC) content is a pivotal aspect of soil health, impacting its physical structure, moisture retention capacity and nutrient-holding capacity (Mesfin *et al.* 2018) [12]. SOC plays a central role in carbon sequestration, making it crucial for climate change mitigation. Agroforestry systems have a remarkable capacity to increase SOC levels through the addition of organic matter from tree leaves, roots and other plant residues. These systems promote the cycling of carbon through both the above-ground and below-ground biomass, thereby contributing to long-term carbon storage (Lorenz and Lal, 2014) [13]. As such, agroforestry not only enhances soil fertility but also plays a significant role in mitigating the effects of climate change by sequestering atmospheric carbon dioxide. The interplay between agroforestry and these critical soil parameters illustrates the intricate relationship between sustainable land management and environmental health (Plieninger *et al.* 2020) [14]. By carefully managing soil pH, EC and soil organic carbon, agroforestry systems can thrive, offering a model for sustainable agriculture that combines tree-based resource management with crop and livestock production. This approach not only boosts agricultural productivity but also nurtures a healthier ecosystem, making it a compelling and vital component of modern agriculture (Fahad *et al.* 2022) [15].

2. Materials and Methods

2.1 Experimental site

The study was conducted at the Forestry Research Farm of Jawaharlal Nehru Krishi Vishwa Vidyalaya, located in Jabalpur, Madhya Pradesh, India. The experiment was carried out within a 14-year-old agroforestry model centered around *Pongamia pinnata*. It spanned two agricultural seasons, specifically the Rabi seasons of 2021-22 and 2022-23. This research farm is situated in the Kymore Plateau and Satpura hill agro-climatic zone, which is characterized by a subtropical climate featuring hot, arid summers and cold, dry winters. The predominant soil type in this region is black, and the topography is gently sloping with a gradient ranging from 0 to 1 percent. The experimental design employed a three-factor double split plot layout. The main plot was divided into two systems: S1, representing an open system, and S2, representing an agroforestry system. The subplot factor encompassed three different sowing dates: D1 (12th November), D2 (27th November), and D3 (12th December). Within each subplot, the sub-subplot factor consisted of two wheat varieties: V1 (MP-3336) and V2 (GW-322). Each treatment combination was replicated three times. The data collected during the experiment underwent statistical analysis of variance using the methodology recommended by Gomez and Gomez in 1984 [16].

2.2 Soil Sample Analysis

Composite soil samples were subsequently transported to the laboratory of the Department of Soil Science and Agricultural Chemistry. Here, standard methodologies were applied to analyze the physico-chemical properties of the soil. The laboratory employed well-established procedures and techniques for assessing each parameter, ensuring the precision and consistency of the results.

2.2.1 Soil pH

A soil-water suspension was prepared by combining 10 grams of soil with 25 millilitres of distilled water, resulting in a ratio of 1:2.5 (soil to water). This suspension was created for the specific purpose of assessing the soil's pH level. To measure the pH, a pH meter was employed, following the procedure outlined by Chopra and Kanwar in 1982 [17]. The pH meter is a conventional instrument utilized for ascertaining the acidity or alkalinity of a solution, in this instance, the soil-water suspension.

2.2.2 Electrical Conductivity

The soil-water suspension originally created for pH measurement also served as the basis for estimating soil electrical conductivity (EC). Following the preparation of the suspension, it underwent a settling process until the supernatant, which is the clear liquid above the settled soil particles, achieved clarity. Subsequently, the EC of the soil-water suspension was quantified using an EC meter, a standard instrument specifically designed for this purpose. The EC meter gauges the electrical conductivity of the solution and quantifies the concentration of dissolved salts and ions, denoted in deci Siemens per meter (dS/m) or siemens per meter (S/m), according to the methodology established by Jackson in 1973 [18]. These EC values hold critical significance in assessing soil salinity and nutrient levels, both of which exert a profound influence on plant growth and agricultural practices.

2.2.3 Organic Carbon

Soil organic carbon content was determined using the Rapid Titration Method, originally devised by Walkley and Black in 1934 [19]. In this procedure, 2 grams of soil sample underwent oxidation with a mixture of potassium dichromate and concentrated sulphuric acid. The heat generated during the dilution of the sulphuric acid facilitated this oxidation process. Subsequently, within the conical flask containing the oxidized soil sample, 200 ml of distilled water and 10 ml of orthophosphoric acid were introduced to ensure appropriate titration conditions. The remaining, unconsumed potassium dichromate was then accurately measured through back-titration, utilizing ferrous ammonium sulphate in the presence of a diphenylamine indicator. This method allowed for the precise quantification of soil organic carbon, a critical parameter indicating organic matter content and soil fertility.

3. Results and Discussion

3.1 Soil pH at different depths under various varieties and sowing dates in agroforestry systems

The effects of distinct land use systems, varying sowing dates, and diverse wheat varieties on soil pH in an agri-silviculture system centered around Pongamia pinnata have been documented in Table 1. The results of this study highlight the significant impact of these factors on soil pH. The research investigates different treatments and their effects on soil pH at a 15 cm depth in open and agroforestry systems. In the open system, the soil pH was 6.54 in the first year and 6.61 in the second year, resulting in a mean value of 6.57. Conversely, the agroforestry system exhibited a pH of 6.22 in the first year and 6.30 in the second year, with a mean pH of 6.26. At a 30 cm depth, the open system had a pH of 6.88 in the first year, 6.90 in the second year, and a mean of 6.89. In contrast, the agroforestry system displayed a pH of 6.42 in the first year, 6.45 in the second year, and a mean pH of 6.44. Notably, the agroforestry systems consistently showed lower pH values compared to open systems, and this difference is statistically significant. This trend is likely attributed to the presence of tree canopies and root exudates in agroforestry systems, which may contribute to soil acidification over time (Singh *et al.* 2002) [20].

Regarding sowing dates, at a 15 cm depth in the first year, Nov. 12 had a pH of 6.36, Nov. 27 exhibited 6.38, and Dec. 12 recorded 6.40. In the second year, Nov. 12 had a pH of 6.43, Nov. 27 showed 6.45, and Dec. 12 had 6.48. The mean values for these dates resulted in soil pH of 6.39, 6.41, and 6.44, respectively. At a 30 cm depth, in the first year, Nov. 12, Nov. 27 and Dec. 12 displayed soil pH values of 6.62, 6.66, and 6.69, respectively. In the second year, these values changed slightly to 6.64, 6.68, and 6.71, with mean values of 6.63, 6.67, and 6.70, indicating a marginal increase in soil pH with later sowing dates. Notably, Dec. 12 showed the highest pH values compared to Nov. 12 and Nov. 27 in both the first and second years, but this difference was not statistically significant (Jat *et al.* 2013) [21].

Lastly, two different wheat varieties, MP-3336 and GW-322, were evaluated for their pH levels. At 15 cm depth, in the first year, MP-3336 had a pH of 6.43, while GW-322 exhibited 6.33. In the second year, these varieties recorded pH values of 6.51 and 6.40, respectively, with mean values of 6.47 and 6.37. Additionally, at a 30 cm depth, MP-3336 had observed soil pH values of 6.69 in the first year and 6.71 in the second year, with a mean of 6.70. For the variety GW-322, these values were 6.62 in the first year and 6.64 in the second year, resulting in a mean pH of 6.63. It is noteworthy that MP-3336 consistently exhibited higher pH values than GW-322, although the statistical analysis indicates a non-significant difference. The observed pH differences in sowing dates and wheat varieties may be influenced by factors such as nutrient uptake, organic matter decomposition, and microbial activity (Burman *et al.* 2009) [22].

Table 1: Soil pH at different depths under various varieties and sowing dates in agroforestry systems

Treatments	Status of soil pH at different depths					
	At 15 cm			At 30 cm		
	2021-22	2022-23	Mean	2021-22	2022-23	Mean
Systems						
S_1- Open	6.54	6.61	6.57	6.88	6.90	6.89
S_2- Agroforestry	6.22	6.30	6.26	6.42	6.45	6.44
SEm±	0.06	0.05	0.05	0.05	0.05	0.05
CD (P = 0.05)	0.34	0.32	0.33	0.32	0.31	0.31
Date of sowing						
D_1- Nov. 12	6.36	6.43	6.39	6.62	6.64	6.63
D_2- Nov. 27	6.38	6.45	6.41	6.66	6.68	6.67
D_3- Dec. 12	6.40	6.48	6.44	6.69	6.71	6.70
SEm±	0.04	0.04	0.04	0.05	0.05	0.05
CD (P = 0.05)	NS	NS	NS	NS	NS	NS
Varieties						
V_1- MP-3336	6.43	6.51	6.47	6.69	6.71	6.70
V_2- GW-322	6.33	6.40	6.37	6.62	6.64	6.63
SEm±	0.04	0.04	0.04	0.03	0.03	0.03
CD (P = 0.05)	NS	NS	NS	NS	NS	NS

3.2 Soil E.C. at different depths under various varieties and sowing dates in agroforestry systems: The impacts on soil electrical conductivity (E.C.) are presented in Table 2, emphasizing the substantial influence of various factors on soil E.C., which remained consistent over the two years of the study and were confirmed by the subsequent average analysis. Beginning with an assessment of land use systems, open and agroforestry systems were compared at a depth of 15 cm. In the first year, the open system exhibited an E.C. of 0.15 dS/m, which increased to 0.18 dS/m in the second year, resulting in a mean E.C. of 0.16 dS/m. In contrast, the agroforestry system displayed a higher E.C., registering 0.21 dS/m in the first year, which further rose to 0.23 dS/m in the second year, yielding a mean E.C. of 0.22 dS/m. At a 30 cm depth, the soil E.C. for the open system measured 0.13 dS/m in the first year, with a slight increase to 0.14 dS/m in the second year, resulting in a mean E.C. of 0.14 dS/m. Conversely, for the agroforestry system, the soil E.C. was higher, recording 0.18 dS/m in the first year, which increased further to 0.21 dS/m in the second year, and a mean E.C. of 0.19 dS/m. This consistent elevation in E.C. for the agroforestry system compared to the open system was statistically significant. The higher E.C. values in the agroforestry system suggest potential differences in salt accumulation, likely influenced by increased nutrient inputs from tree litter and potential root exudation (Dahiya *et al.* 2022) [23].

Examining various sowing dates, namely, Nov. 12, Nov. 27 and Dec. 12, the E.C. in the first year for these dates was 0.17, 0.18, and 0.18 dS/m, respectively, which increased in the second year to 0.20, 0.21, and 0.21 dS/m. The mean E.C. values for each of these sowing dates were 0.19 dS/m at 15 cm depth. Considering the soil E.C. at a 30 cm depth, for Nov. 12, Nov. 27, and Dec. 12 in the first year, values were 0.15, 0.15, and 0.16 dS/m, respectively. In the second year, the soil E.C. slightly increased to 0.17, 0.18, and 0.18 dS/m for Nov. 12, Nov. 27, and Dec. 12, respectively, with mean values of 0.16 dS/m. However, despite the slightly higher E.C. observed with Nov. 27 and Dec. 12, the differences between the sowing dates were not statistically significant. These findings indicate that the impact of varying sowing dates on E.C. was limited, highlighting that short-term fluctuations in soil salinity were not substantial. This underscores the complexity of factors influencing soil salinity, including irrigation practices, nutrient management and soil drainage (Venkanna *et al.* 2014) [24].

Further two wheat varieties, MP-3336 and GW-322, were examined. At 15 cm soil depth, the E.C. values for these varieties were 0.17 and 0.18 dS/m, respectively, in the first-year which increased in the second year to 0.20 and 0.21 dS/m at 15 cm depth. The mean E.C. for both varieties was 0.19 dS/m. At a 30 cm depth, the first-year E.C. values for MP-3336 and GW-322 were 0.15 and 0.16 dS/m, respectively, which increased in the second year to 0.17 and 0.18 dS/m, respectively, resulting in mean E.C. values of 0.16 dS/m. The E.C. values at 30 cm depth were slightly lower compared to the 15 cm depth, indicating that the deeper soil layer had a relatively lower salinity level. Although there was a slightly higher E.C. for GW-322 compared to MP-3336, the difference was statistically non-significant. This suggests that these wheat varieties exhibit a comparable level of salinity tolerance. Wheat plants are known to have varying degrees of tolerance to soil salinity, and the fact that these two varieties responded similarly indicates their ability to adapt to moderate salinity levels (Singh *et al.* 2018) [25].

Table 2: Soil E.C. at different depths under various varieties and sowing dates in agroforestry systems

Status of Soil Electrical Conductivity at different depths (dS/m)						
Treatments	**At 15 cm**			**At 30 cm**		
	2021-22	**2022-23**	**Mean**	**2021-22**	**2022-23**	**Mean**
Systems						
S_1- Open	0.15	0.18	0.16	0.13	0.14	0.14
S_2- Agroforestry	0.21	0.23	0.22	0.18	0.21	0.19
SEm±	0.01	0.01	0.01	0.01	0.01	0.01
CD (P = 0.05)	0.06	0.05	0.05	0.04	0.04	0.04
Date of sowing						
D_1- Nov. 12	0.17	0.20	0.19	0.15	0.17	0.16
D_2- Nov. 27	0.18	0.21	0.19	0.15	0.18	0.16
D_3- Dec. 12	0.18	0.21	0.19	0.16	0.18	0.17
SEm±	0.01	0.01	0.01	0.01	0.01	0.01
CD (P = 0.05)	NS	NS	NS	NS	NS	NS
Varieties						
V_1- MP-3336	0.17	0.20	0.19	0.15	0.17	0.16
V_2- GW-322	0.18	0.21	0.20	0.16	0.18	0.17
SEm±	0.01	0.01	0.01	0.01	0.01	0.01
CD (P = 0.05)	NS	NS	NS	NS	NS	NS

3.3 Changes in status of soil organic carbon at various soil depths under different varieties and sowing dates in agroforestry systems: The study conducted an assessment of multiple treatments and their effects on soil organic carbon content at two different depths (15 cm and 30 cm), as presented in Table 3. Regarding the land use systems, at a depth of 15 cm, the open system displayed an organic carbon content of 0.52% in the first year and 0.55% in the second year, resulting in an average of 0.53%. In contrast, the agroforestry system exhibited significantly higher organic carbon content, with values of 0.69% in the first year, 0.71% in the second year, and an average of 0.70%. At a depth of 30 cm, the open system showed an organic carbon content of 0.49% in the first year and maintained similar levels in the second year. In contrast, the agroforestry system displayed higher organic carbon content with values of 0.67% in the first year and 0.69% in the second year, resulting in an average of 0.68%. These results revealed a statistically significant difference between the two systems. The consistent trend of higher organic carbon content in agroforestry systems suggests the potential benefits of carbon sequestration through tree-crop integration. This positive impact is likely due to the input of organic matter from tree leaves, root turnover, and microbial activity associated with tree-root zones (Gupta and Sharma, 2012) [26].

In terms of the influence of sowing dates, Nov. 12, Nov. 27 and Dec. 12 were examined at both 15 cm and 30 cm depths. At 15 cm, the organic carbon content for these dates was 0.61%, 0.62%, and 0.60%, respectively, in the first year. These values increased slightly in the second year to 0.63%, 0.63%, and 0.62%. The average organic carbon content for these dates was 0.62%. At 30 cm, the organic carbon content for Nov. 12 and Nov. 27 remained consistent, with values of 0.59% for the first and second years, resulting in a mean of 0.59%. Sowing on Dec. 12 exhibited slightly lower values with 0.57% and 0.58% for the first and second years, with the mean remaining at 0.58%. Despite minor variations in organic carbon content among the different sowing dates, these differences were not statistically significant. This implies that the choice of sowing date within the specified range did not significantly impact soil organic carbon content at either the 15 cm or 30 cm soil depths. These findings suggest that other factors, such as soil properties and agricultural practices, may exert a more dominant influence on organic carbon levels in this agroforestry model (Rasmussen and Parton, 1994) [27].

Finally, two wheat varieties, MP-3336 and GW-322, were studied. At 15 cm depth, the organic carbon content of MP-3336 was 0.60% in the first year and 0.62% in the second year, resulting in an average of 0.61%. GW-322 exhibited a slightly higher average, with 0.61% in the first year, 0.63% in the second year, and an average of 0.62%. At 30 cm depth, both varieties displayed similar figures, with 0.58% for MP-3336 and 0.59% for GW-322 in the first year and 0.59% for MP-3336 and 0.60% for GW-322 in the second year, resulting in means of 0.58% for MP-3336 and 0.59% for GW-322. Although GW-322 consistently exhibited slightly higher organic carbon content values compared to MP-3336, the statistical analysis indicates that this difference is not statistically significant. This implies that the observed disparities in organic carbon content between the two wheat varieties fell within the range of natural variability and did not reach the level of statistical significance (Van de Broek *et al.* 2020) [28].

Table 3: Changes in status of soil organic carbon at various soil depths under different varieties and sowing dates in agroforestry systems

Status of Soil Organic Carbon at different depths (%)						
Treatments	**At 15 cm**			**At 30 cm**		
	2021-22	**2022-23**	**Mean**	**2021-22**	**2022-23**	**Mean**
Systems						
S_1- Open	0.52	0.55	0.53	0.49	0.49	0.49
S_2- Agroforestry	0.69	0.71	0.70	0.67	0.69	0.68
SEm±	0.01	0.01	0.01	0.01	0.01	0.01
CD (P = 0.05)	0.03	0.03	0.03	0.03	0.03	0.03
Date of sowing						
D_1- Nov. 12	0.61	0.63	0.62	0.59	0.60	0.59
D_2- Nov. 27	0.62	0.63	0.62	0.59	0.60	0.59
D_3- Dec. 12	0.60	0.62	0.61	0.57	0.58	0.58
SEm±	0.01	0.01	0.01	0.01	0.01	0.01
CD (P = 0.05)	NS	NS	NS	NS	NS	NS
Varieties						
V_1- MP-3336	0.60	0.62	0.61	0.58	0.59	0.58
V_2- GW-322	0.61	0.63	0.62	0.59	0.60	0.59
SEm±	0.01	0.01	0.01	0.01	0.01	0.01
CD (P = 0.05)	NS	NS	NS	NS	NS	NS

4. Conclusion

In conclusion, agroforestry emerges as a transformative and sustainable land management approach with profound impacts on soil properties. This integrated system, combining agriculture with strategic tree inclusion, has the potential to significantly influence soil pH, electrical conductivity and soil organic carbon content. The findings from the study underscore the vital role of agroforestry in enhancing soil health, nutrient availability and mitigating soil salinity, all while actively contributing to carbon sequestration for climate change mitigation. Agroforestry represents a compelling model for modern agriculture, bridging the gap between agriculture and forestry, promoting biodiversity, and sustaining rural livelihoods. As environmental concerns intensify, this ancient practice gains renewed significance, offering a promising solution to the challenges of sustainable land management and environmental health on a global scale.

5. Future Scope

The future trajectory of agroforestry research presents exciting avenues for scientific exploration. Longitudinal studies spanning several decades are imperative to unravel the enduring impact of agroforestry systems on soil properties and ecosystem dynamics. Investigating diverse agroforestry models, crop-specific interactions and their influence on soil microbial communities will contribute to a holistic understanding of this field. Furthermore, research must delve into how agroforestry systems bolster soil resilience in the context of evolving climate patterns, while also serving as a robust mechanism for carbon sequestration to mitigate climate change. Furthermore, exploring synergies between agroforestry and other sustainable agricultural practices and assessing their applicability across various agroclimatic regions on a global scale are pivotal areas of future inquiry.

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