Altitudinal wise assessment of soil physio-chemical properties of different agroforestry systems in Garhwal Himalaya, India

Ng Manitombi Devi[1*], Himshikha Gusain[2], Bhagyashree Debbarma[3] and Rekha Rana[4]

ABSTRACT: *Agroforestry systems significantly influence soil properties, which are important indicators of soil health. The study was carried out to assess soil properties viz., moisture content, water-holding capacity, soil texture, bulk density, and chemical properties like pH, SOC, SCS and SOM in three prominent agroforestry systems including agrihorticulture (scattered fruit crops), agrisilviculture (tree on bunds), and agrisilvihorticulture (homegarden) of Western Himalayas, Uttarakhand. Soil samples were collected from three elevations (800-1300m, 1300-1800m, and above 1800m) under agroforestry systems at two depths (0-15cm, 15-30cm). The results show that altitude significantly influences soil texture, with sand content increasing and clay content decreasing with elevation. Higher altitudes exhibited greater soil moisture and organic matter retention. The Agri-silvi-horticulture system, particularly at higher altitudes, demonstrated superior water-holding capacity, lower bulk density, and higher SOC and SOM, making it the most effective for improving soil quality. Conversely, the Agri-horticulture system at lower elevations had higher bulk density and lower organic carbon content. Soil organic carbon stock (SCS) declined with depth, with the highest values observed in the topsoil. This study emphasizes the potential benefits in enhancing soil fertility, moisture retention, and carbon sequestration, emphasizing the importance of selecting appropriate systems for adapting to climate change and promoting sustainable land management in the Himalayan region. The findings provide valuable insights for improving agroforestry practices in the region to promote soil health and agricultural productivity.*

Research Communication

ARTICLE INFO

Received: 03.02.2025

Accepted: 23.06.2025

Keywords:
*Agroforestry,
Soil,
Physical chemical properties,
Carbon sequestration,
Climate change,
Sustainable management*

1. INTRODUCTION

Over the past few decades, the soils, particularly from the Himalayan zone, have attracted more attention to their potential to bear global environmental change through varied land use systems and management. Various land management practices, such as agriculture (irrigated and rainfed), horticulture, and forestry practices, affect soil properties, along with its nutrient composition (Matano *et al.,* 2015). Agroforestry systems (AFSs) are developed for economic purposes, but they can also play a significant role in maintaining ecological equilibrium and store C in perennial vegetation and soil. Implementing agroforestry has shown great potential to mitigate carbon emissions and enhance soil quality in the Himalayan region (Verma *et al.*, 2023). Trees in AFS are capable of effectively sequestering atmospheric carbon in both tree biomass and soil. The organic matter from decomposing litterfall enhances the soil physiochemical properties, including water-holding capacity, pH, and SOC. Several studies have investigated the relationship between trees and soil properties. Nizam *et al.* (2006) found that *Macaranga lowii* and *Kayea ferrea* are strongly associated with phosphorus (P) availability, while *Garcinia pyrifera* is closely linked to potassium (K) availability. Other factors, such as soil temperature, slope aspect, vegetation, and altitude, can also affect soil properties (Bardelli *et al.,* 2017).

Furthermore, inquiries have highlighted the varying impact of climate changes along elevational gradients on soil characteristics (Trujillo-González *et al.,* 2022). Researches have shown that carbon and nitrogen levels tend to rise with altitude, and these elements are directly related with temperature and rainfall (Zhang *et al.,* 2021). Consistent with this, soil temperature, pH, electrical conductivity, and the C:N ratio generally rise with altitude (Hamid *et al.,* 2020). Simon *et al.* (2018) also observed a direct relationship between soil carbon levels, pH, and altitude. Climate change impacts plant composition and biomass, causing changes in characteristics of soil and species distribution.

Ng Manitombi Devi
dmani4481@gmail.com

[2] Assistant professor

[1,3&4] PhD scholar

Department of Forestry, Hemvati Nandan Bahuguna Garhwal University Srinagar, Pauri Garhwal, Uttarakhand 246174

Agroforestry offers a balanced approach by enhancing carbon storage and enriching soil nutrients, potentially boosting agricultural productivity. Agroforestry is an essential approach for meeting climate change adaptation and mitigation goals. According to (FAO 2009), Agroforestry practices can be crucial in combating climate change by capturing carbon in vegetation and soil. Due to its holistic approach, Agroforestry is recognized as a way to reduce greenhouse gas (GHG) emissions under the Kyoto Protocol. This recognition is attributed to carbon capture and utilization efficiency, which results in enhanced carbon sequestration (Semere *et al.*, 2022). Studies have shown that the agroforestry systems play a crucial role in boosting agricultural productivity and soil fertility, helping to preserve soil organic matter and support nutrient cycling. The agroforestry systems (AFS) in the western Himalayas vary and are influenced by factors like altitude, climate, and topography. Vegetation is crucial in soil formation and its properties, as plant tissues serve as the primary source of soil organic matter, therefore acting as the key determinant of the physiochemical properties of soil like pH, water holding capacity soil texture, nutrients, etc. and their influence on plant growth. Furthermore, the development of vegetation relies on the soil's ability to supply nutrients, as the selective uptake of nutrient by various tree species and their ability to return them to the soil lead to changes in soil properties.

The Western Himalayas cover an area of 331,392 square kilometers, encompassing the states of Jammu & Kashmir, Himachal Pradesh, and Uttarakhand. The zone has varied climatic conditions, with significant variations in nutrient content. Although some studies have evaluated and quantified changes in altitude and component soil nutrient levels in different regions of India, the Western Himalayas have not been thoroughly studied at a regional scale. Also, no systematic attempts have been made to compare the elevational soil properties in different agroforestry systems of Garhwal Himalaya. This research investigates soil characteristics of key agroforestry systems to support their management and the implementation of diverse agroforestry practices. Despite progress in agroforestry research, there is a gap in region-specific studies that can verify the productivity and sustainability of specific agroforestry systems in content with attitudinal change. The current study sought to estimate the soil physiochemical properties under different agroforestry systems in the hills of the Western Himalayan zone, Uttarakhand. The aim of the study are (i) to evaluate the physical and chemical soil properties of various agroforestry systems at different altitudes and (ii) to estimate altitudinal variation on SOC potential of soil under selected agroforestry systems along an altitude. We hypothesized that altitudinal-wise, soil physio-chemical properties would also change significantly under different agroforestry systems.

2. MATERIALS AND METHOD

2.1 Study area:

The current study was carried out in farmers' fields of Pauri district and Rudraprayag district 30.28°*N 78.98°E and* 30.15°N to 78.78°E with elevations ranging from 800m to more than 1800m. The experiment site is situated in the mid-hills subtropical and sub-temperate zone of Uttarakhand, India (Fig. 1).

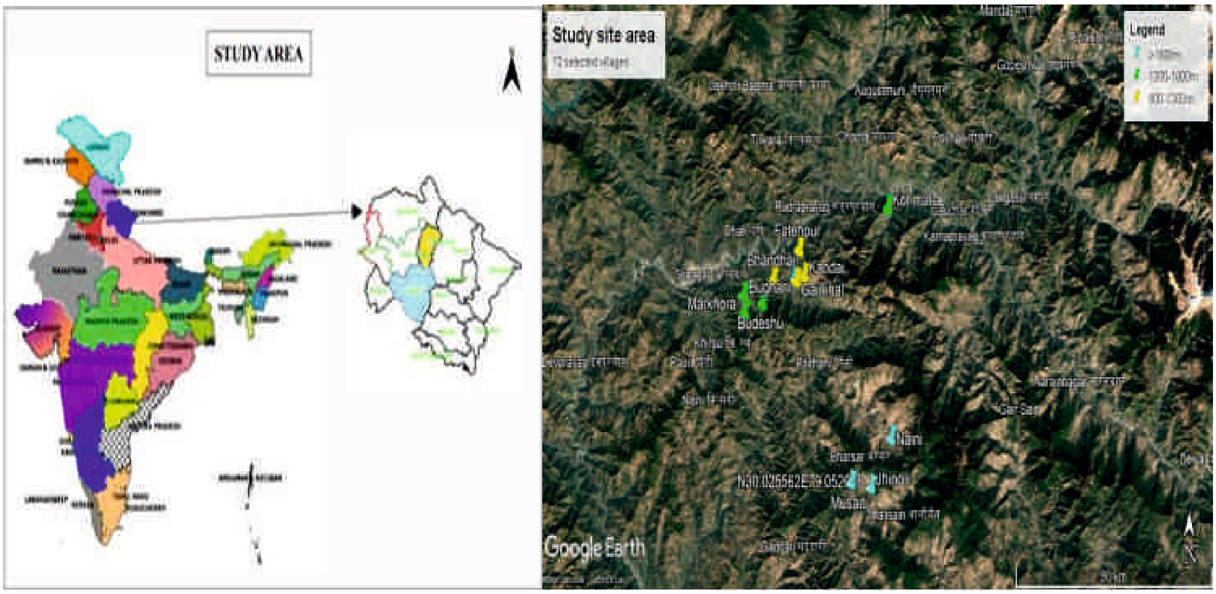

Fig 1: Map of study area

In Rudraprayag, the mean annual rainfall is 637mm, and the average temperature rises to 29°C in summers and falls up to -3°C in the winters. In Pauri district, the average rainfall is 172.88mm, and temperature ranges from 26°C to 14°C.

Three elevation ranges were selected: lower (800-1300 m), mid (1300-1800 m), and upper (above 1800 m). At each elevation, there are three agroforestry systems with different models: Agrihorticulture (Bhimal-based, Ficus+Bhimal, and Oak-based), Agrisilviculture (Malta + Bhimal + Oak + Gmelina, Walnut + Malta + Bhimal + Napati, and Oak + Malta + Peach), Agrisilvihorticulture (Malta based, Malta-based and Apple + Malta) with two depth levels (0-15 cm) and (15-30 cm) were categorized (Table 1).

The agroforestry fields were selected at three altitudes *viz.* low (800-1300 m), mid (1300-1800 m), and upper elevation (>1800 m) (Table 1). At each altitude, based on the level of the system, agroforestry was categorized as Agri-silviculture (Tree on bunds), Agri-horticulture (Scattered trees of fruit crops), and Agri-silvi-horticulture (Homegarden), (Table 2). Selected models are Bhimal-based, Ficus+Bhimal, Oak-based, Malta+Bhimal+Oak+Gmelina, Walnut+Malta+Bhimal+Napati, Oak+Malta+Peach, Malta based, Malta-based and Apple+Malta (Table 2).

2.2 Methodology

The soil samples were collected during April–June 2024. Soil sampling was done randomly collected from each system at two depths, 0–15 cm and 15–30 cm, using a soil corer. Fifty-four samples (3 altitude × 3 Agroforestry system × 2 depth × 3 replicates (Salve *et al.,* 2018) were collected from the site. Then, the samples was air-dried at room temperature, and any visible organic material, stones, plant roots, and other debris were carefully removed. The Physical properties of soil include Moisture content, Water holding capacity, Soil texture, Texture class, Soil bulk density, chemical properties pH, Soil organic carbon, Soil carbon stock, and Soil organic matter were studied and followed all standard procedures to explore the impact of trees on soil properties under selected agroforestry systems (Table 3).

2.3. Computations and statistical analysis

The soil analysis data was collected and organized for statistical analysis using Microsoft Excel 2007. The relationship between soil physio-chemical properties and altitude, agroforestry system, and soil depth was determined through Pearson's correlation matrix using the OPSTAT statistical analysis tool (www.hau.ernet.in). The data in the tables are presented as the mean of three replicates ± standard error (SE). Principal Component Analysis (PCA) was further applied to identify which soil properties influence the outcome using OriginLab software (Version 10.2).

3. RESULTS AND DISCUSSION

3.1 Soil texture (%) and texture class

At lower elevations (800-1300m), maximum sand percentage was found in the Malta based model, where minimum was observed in the Bhimal based model, while clay percentage was observed more in the Bhimal model and less in the Malta model. The silt was present more in Malta + Bhimal + Oak + Gmelina at 15-30cm depth, and at 0-15cm Malta-based have a high amount of silt. Silt percentage increased with depth, clay percentage decreased with increasing depth, and sand percentage increased with depth in

Table 1. Selection of study sites

Altitude range/ Agro-ecological zones	Study sites	Altitude (m)	Longitude	Latitude	Availability of Agroforestry systems		
					AS	AH	ASH
Humid subtropical zone	Fatehpur	850m	N30°14.080’	E078°56.277’	+	-	+
(800-1300m)	Kandaii	1050m	N30º12.696’	E078º56.767’	+	-	+
	Bhandhai	1280m	N30º12.497’	E078º53.862’	+	+	+
	Gairkhal	1300m	N30º12.448’	E078º56.046’	+	+	+
Dry Subtropical zone	Kotmalla	1380m	N30º16.297’	E079°04.535’	+	+	+
(1300-1800m)	Bughani	1400m	N30º11.658’	E078º51.110’	+	-	+
	Markhora	1480m	N30°10.770’	E078°51.198’	+	-	+
	Budeshu	1600m	N30º11.242’	E078º52.892’	+	+	+
Temperate zone	Jhinoli	1850m	N30º1.53372’	E079º3.12288’	+	+	+
(Above 1800m)	Jundoli	1900m	N30º12.494’	E078º55.768’	+	+	+
	Musaiti	2050m	N30º01.794’	E079°01.241’	+	+	+
	Naini	2100m	N30°04.139’	E079°04.991’	+	+	+

AS= Agri-silviculture system, AH=Agri-horticulture system and ASH=Agri-silvi-horticulture system

Bhimal-based and Malta + Bhimal + Oak + Gmelina, while it had shownshowed a decreasing pattern in Malta-based agrofrestry. There was no change in soil texture class with a depth of Bhimal-based (clay) and Malta-based (sandy clay loam) whereas Malta + Bhimal + Oak + Gmelina agroforestry model showed changes with depth at 0-15 cm clay and 15-30cm it was loam.

At midddle elevations (1300-1800m), Ficus + Bhimal had maximum sand and minimum clay percentage while Walnut+Malta+Bhimal+Naspati hadmaximum clay and minimum sand percentage. Silt percentage was high in Malta-based at 15-30cm and low in Walnut + Malta + Bhimal + Naspati at 0-15cm. No variation was found in soil texture class and soil percentage with depth in all systems. The soil texture observed in Walnut + Malta + Bhimal + Naspati was clay, and the sandy clay was in Ficus+Bhimal and Malta-based agroforestry models.

Above 1800 m, the maximum percentage of sand was found in Oak+Malta+Peach and the minimum in the Oak+Malta agroforestry model. Silt had a low rate in Oak+Malta+Peach and high in Apple+Malta at 0-15 cm and 15-30 cm Oak-based agrofroestry. The sand and silt percentage increased with depth in the Oak+Malta+Peach and Oak model but decreased in the Malta based model, whereas the clay percentage decreased in the Oak+Malta+Peach and Oak model but increased in the Apple+Malta model. The soil texture class remained consistent across all systems. Over time, the physio-chemical properties of soil are influenced by topography, climate, and vegetation. The result confirmend that and content increased in the ASH system at deeper depths, contributing to better drainage and supporting root development. The sand, silt, and clay proportions change across the altitudinal gradient (Table 4). Sand content exhibited a strong positive relationship with altitude, whereas silt and clay content negatively correlated with altitude. Similar findings were reported by Kamal *et al.* (2023), who noted that sand content is lower at the bottom and mid elevations due to reduced soil erosion.

3.2 pH, Moisture content (MC), Water holding capacity (WHC), and Bulk density (BD)

At 800-1300m, the Malta+Bhimal+Oak+Gmelina-based agroforestry system showed the highest pH, while the Bhimal-based system showed the minimum. Malta-based had maximum moisture content and minimum Bhimal-based. Malta+Bhimal+Oak+ Gmelina model showed the highest WHC% at 0-15 cm (49.86%) and the lowest at 15-30cm (27.33%). Malta-based at 15-30 cm (38%) showed maximum and minimum at 0-15 cm (36.34%). Malta-based exhibited the highest bulk density and the lowest in the Malta+Bhimal+Oak+Gmelina. pH, moisture content, and Bulk density increase with depth while Water holding capacity decreased with depth.

At 1300-1800m, Malta-based showed the highest pH and minimum in the Ficus+Bhimal agroforestry system. The Malta-based system had maximum moisture content and minimum in Ficus+Bhimal. Maximum WHC% showed in Ficus+Bhimal at 0-15cm (42.44%) and minimum in Malta-based at 15-30 cm (26.56%). Bulk density was high in Malta-based at 15-30 cm (1.83 g/cm^3) and low in Walnut+Malta+ Bhimal+Naspati at 0-15cm (1.45 g/cm^3). pH and bulk density increase with depth while Water-holding capacity and moisture content decrease.

Above 1800m, Oak+Malta+Peach had high pH and is low in Oak-based. Moisture content was maximum in Oak+Malta+Peach and minimum in Apple + Malta. Water holding capacity was high in Oak+Malta+ Peach at 0-15 cm (54.98%) and minimum at 15-30 cm (34.49%). Bulk density was maximum in Apple+Malta at 0-15cm (1.98 g/cm^3) and minimum at 15-30 cm (1.44 g/cm^3. pH showed an increasing pattern with depth and moisture content, and Water holding capacity showed a decreasing pattern except for Apple+Malta model. In contrast, Bulk density showed an opposite pattern compared to Water holding capacity and moisture content (Table 5). Soil moisture content was high in higher elevations and the Agri-silvi-horticulture system. Soil moisture content was influenced by the availability of irrigation. The surface layer (0–15 cm) had higher moisture levels than the sub-surface layer (15–30 cm), likely due to a greater accumulation of crop residue and organic matter in the topsoil. These results support with the results of Dahiya *et al.* (2022) who explained the effect of saturated hydraulic conductivity under different agroforestry systems, soil depth, and their interaction was significant.

The water holding capacity (WHC) was greater in Agri-silvi-horticulture system, likely due to the thick litter layer on the ground and the more significant accumulation of organic matter due to higher species richness and density. WHC lowered with increasing soil depth, with the surface (0-15 cm) layer showing the highest values across all home gardens. The percentage of clay was maximum in all Agri-silvi-horticulture systems. (Gomez *et al.,* 2002) study, the water-holding capacity of clay and the high permeability of sand may explain the specific relationship between clay, sand, and moisture content in soil.

Bulk density decreased with increasing elevation. The lower bulk density at higher altitudes may be attributed to the combined use of organic and inorganic fertilizers, which help improve soil bulk density. Bulk density (g/cm3) was observed highest in the subsurface layer, followed by the top surface layer. These findings are supported by Singh *et al.* (2011). Bulk density was maximum in the Agri-horticulture system in lower elevations. The plausible reason for higher bulk density in the Agri-horticulture system may be more tillage operations for cultivating crops and low litterfall input. Meanwhile, Kundan (2024) recorded the highest bulk density in the Agrisilviculture system due to minimum litterfall accumulation.

Among three different systems, the Agri + silvi + horticulture system recorded the highest and lowest in the Agri-horticulture system. The slightly acidic pH in the Agri-horticulture system can be attributed to the high organic content, its accumulation, and the gradual decomposition process, which releases organic acids that lower the pH. Similar findings were observed by Mehraj *et al.* (2022), who reported lower pH under high canopy cover because of the release of organic substances during litter deterioration. Also, soil pH showed a higher value at the low layer layer than the top layer in all agroforestry systems because tree root abundance is high at the surface layer (Maqbool *et al.,* 2017).

3.3 Soil organic carbon (SOC)

Soil organic matter and organic carbon were maximum in Malta + Bhimal + Oak + Gmelina and minimum in the Bhimal based. The Malta-based model had high soil carbon stock at 0-15 cm (76.61) and at 15-30 cm Bhimal based (42.75), where soil carbon stock was high in Bhimal based at 15-30 cm (36.60) and (35.88) at 0-15 cm in Malta + Bhimal + Oak + Gmelina. Soil organic matter, organic carbon, and carbon stock decrease with the rise in soil dept at 1300-1800m, the Ficus+bhimal model showed minimum soil organic matter, soil organic carbon, and soil carbon stock. Malta-based model at 15-30 cm (2.75%) and Walnut + Malta + Bhimal + Naspati at 0-15 cm (2.17%) have maximum soil organic matter. Malta-based at 15-30 cm (2.11%) and Malta + Bhimal + Naspati at 0-15 cm (1.74%) showed high Soil organic carbon. Charan *et al.* (2012) found a positive correlation between SOC and altitude. They observed a decline in SOC content with increasing soil depth, with the highest SOC recorded at the 0-15 cm depth across all agroforestry systems. Some researchers have noted a similar trend of SOC decreasing with increasing soil depth (Singh *et al.,* 2021).

3.4 Soil carbon stock (SCS)

The highest SCS was recorded in Malta-based at 15-30 cm (60 t ha^{-1}) and Malta+Bhimal+Naspati at 0-15 cm (36.65 t ha^{-1}). SOM, SOC, and SCS increased with depth in all systems except the Bhimal+Ficus agroforestry model. The increase of SCS stocks in topsoil in Agroforestry systems is due to higher broadleaf tree species than coniferous species (Mayer *et al.,* 2022). Across the different systems, the maximum value of SCS (64.38 t ha^{-1}) was observed in the Agri-silvi-horticulture system, while the minimum value (15.67 t ha^{-1}) was observed in Agri+silvi. This may be due to adding more inorganic fertilizers than organic fertilizers (Bargali & Bargali, 2020). The decline in soil carbon with elevating soil depth could be due to slow carbon flow and soil compaction at deeper levels (Dar & Somaiah, 2015). Due to continuous addition of partially decomposed plant and animal matter in the surface layer the SCS decreases with soil depth.

3.5 Soil organic matter (SOM)

Over 1800 m of SOM and SOC were observed high in Apple+Malta models at 0-15 cm and low at 15 -30 cm. Oak+Malta+Peach showed maximum soil carbon stock and minimum in the Oak-based agroforestry model. With increasing depth, the SOM, SOC and SCS decrease. Soil organic matter is essential for influencing soil's physical, chemical, and biological characteristics, creating an environment that supports biological activity and life. Once depleted, it generally takes a long time to recover. The differences in organic matter levels across the study sites may be due to variations in plant species composition and the amount of organic material on the soil surface (Sahoo, 2020). As altitude increased, temperatures drop, which reduces microbial activity. This leads to a slower rate of SOM decomposition, causing plant-derived SOM to be more effectively stored in the soil, especially in tropical and subtropical regions (Sundqvist *et al.,* 2013). Organic matter varies with the study sites, likely due to differences in vegetation composition and the amount of biomass on the top layer. For example, the Agri-silvi-horticulture system, which had a greater variety of plant species, produced more litter, leading to higher organic matter at the site. Additionally, the accumulation of humus, other waste materials, and the incorporation of plant debris may have contributed to the increased organic matter (Pinho et al., 2010). They are also associated with It has also been linked to higher concentrations of SOM as Dori *et al.* (2022) found that home garden (AHS) systems positively impact soil properties.

Table 2. Description of selected agroforestry systems and their components

System name	Elevation	Major trees species	Models	Major horticulture species	Major crops	
					***Rabi* crops**	***Khariff* crops**
Agri-silviculture system (Tree on bunds)	Low.	*Grewia oppositifolia*	Bhimal based	-	*Triticum aestivum Brassica campestris* L., *Eleusine coracana*	*Oryza sativa, Cajanus cajan, Echinochloa frumentaceae*
	Mid.	*Grewia oppositifolia, Ficus palmata, Melia azedirach*	Ficus+ Bhimal			
	Upp.	*Ficus auriculata, Quercus leucotrichophora*	Oak based			
Agri-horti-silviculture system (Homegarden)	Low.	*Citrus sinensis, Prunus domestica, Musa accuminata*	Malta+ Bhimal+ Oak+ Gmelina	*Grewia oppositifolia, Gmelina arborea, Grewia oppositifolia, Ficus palmata, Holoptelea integrifolia*	*Allium sativum, Pisum sativum, Brassica oleracea* var, *Solanum tuberosum*	*Capsicum annum* L., *Phadeolus valgaris, Lagenaria siceraria*
	Mid.	*Pyrus communis, Citrus sinensis, Juglans regia*	Walnut+ Malta+ Bhimal+ Napati,	*Ficus palmate, Quercus leucotricho-phora*		
	Upp.	*Malus domestica, Citrus sinensis, Juglans regia, Pyrus communis, Prunus persica*	Oak+ Malta+ Peach	*Ficus auriculata, Quercus leucotricho-phora*		
Agri-horticulture system (Scattered fruit crops)	Low.	*Citrus sinensis*	Malta based	*Citrus sinensis, Psidium guajava, Prunus persica, Pyrus communis, Phyllanthus emblica*	*Brassica oleracea* var *Raphanus sativus* L.	*Capsicum annum, Zea mays*
	Mid.	*Citrus sinensis*	Malta based	*Citrus sinensis, Juglans regia*		
	Upp.	*Citrus sinensis + Malus domestica*	Apple+ Malta	*Malus domestica, Citrus sinensis, Juglans regia, Citrus aurantium, Citrus pseudolemon*		

Low=Lower elevation (800-1300m), Mid= Middle elevation (1300-1800m) and Upp=Upper elevation (>1800m).

3.6 Correlation matrix for physio-chemical properties of soil

Clay and Sand were strongly inversely related, meaning higher sand content typically led to lower clay content, and vice versa, with silt being positively correlated to Sand but negatively correlated to clay content. SOC and SOM were strongly correlated, indicating that more organic matter led to more

Table 3. Parameters used to evaluate the physio-chemical properties of soil

S.No.	Soil parameter	Formula/Method	Reference
1.	Moisture content (%)	$\frac{\text{Fresh weight of soil (g)} - \text{dry weight of soil (g)}}{\text{Dry weight of soil (g)}} \times 100$	Upreti (2019)
2.	Water holding capacity (%)	$\frac{W2-W3-W4}{W3-W1} \times 100$	Upreti (2019)
3.	Soil texture and class	$\frac{\text{Weight of sieved soil proportion}}{\text{Total soil sample weight}} \times 100$ Class: Based on texture percentage values and assessed by using texture triangle method	USDA (2017)
4.	Soil bulk density (g/cm^3)	Dry soil weight (g)/ Soil volume (cm^3) Soil volume (cm^3) = 3.14 x radius2 x ring height (h)	ISO (2017)
5.	Soil pH	Determined using dynamic digital pH meter	Jackson (1973)
6.	Soil organic carbon (%)	10 (B-T) X 0.003 x 100 B weight of soil (g)	Walkley & Black (1934)
7.	SOC Stock ($t\ ha^{-1}$)	Soil bulk density x Soil depth x SOC (%)	Pearson (2007)
8.	Soil organic matter (SOM)	SOM% = Soil organic carbon (%) × 1.724.	Budiman *et al.,* (2020)

Table 4: Soil texture and soil texture class as influenced by soil depth, agroforestry system and altitude.

Altitude	System	Agroforestry Models	Depth	Soil texture (%)			Soil Texture class
				Sand	Silt	Clay	
800-1300m	AS	Bhimal based	0-15	42.30±3.47	6.74±0.70	50.94±3.54	Clay
			15-30	42.51±2.49	7.09±0.52	50.39±2.52	Clay
	ASH	Malta+ Bhimal+ Oak+ Gmelina	0-15	46.58±5.83	7.74±0.07	45.67±5.67	Clay
			15-30	49.43±3.43	8.09±0.09	42.46±3.53	Loam
	AH	Malta based	0-15	59.43±5.10	7.70±0.46	32.86±5.30	Sandy clay loam
			15-30	57.47±5.02	15.41±7.91	27.10±6.90	Sandy clay loam
1300-1800m	AS	Ficus+ Bhimal	0-15	47.57±3.75	8.53±0.60	43.88±3.72	Sandy clay
			15-30	48.58±6.59	8.31±0.27	43.10±6.53	Sandy clay
	ASH	Walnut+ Malta+ Bhimal+ Naspati	0-15	44±7.36	6.56±0.82	49.43±7.30	Clay
			15-30	45.03±5.56	7.66±0.64	47.29±6.17	Clay
	AH	Malta based	0-15	47.19±2.23	7.52±1.10	45.28±3.30	Sandy clay
			15-30	46.01±2.11	7.03±0.98	46.95±2.30	Sandy clay
Above 1800m	AS	Oak based	0-15	62.75±2.46	11.67±1.50	25.57±1.14	Sandy clay loam
			15-30	62.76±2.54	12.06±1.55	25.16±1.24	Sandy clay loam
	ASH	Oak+ Malta+ Peach	0-15	65.16±3.80	8.88±0.79	25.94±3.49	Sandy clay loam
			15-30	67.73±1.04	9.22±0.53	23.03±0.79	Sandy clay loam
	AH	Apple + Malta	0-15	58.96±13.18	13.18±1.58	27.84±4.27	Sandy clay loam
			15-30	56.91±4.98	11.52±0.84	31.55±4.81	Sandy clay loam

AS=Agri-silviculture system, AH=Agri-horticulture system and ASH=Agri-silvi-horticulture system organic carbon in the soil. Soil moisture was positively correlated with clay, showing that soils with more clay retained more moisture. Conversely, Sand tended to reduce moisture content. The pH was only weakly correlated with most variables, but it was positively related to SOC and SOM. The SOC and SOM showed a positive significant association ($p < 0.01$) with pH. Changes in soil pH can influence the availability of soil nutrients and the nutritional health of vegetation. The percentage of silt showed a positive correlation ($p < 0.01$) with sand, and the percentage of clay showed a negative relationship ($p<0.01$) with the percentage of sand and silt. However, Hu *et al.* (2019) found that the percentage of sand had a positive

Table 5. Soil pH, Moisture content (MC), Water holding capacity (WHC) and Bulk density (BD)

Altitude	System	Models	Depth	pH	MC%	WHC%	BD (g/cm^3)
800-1300m	AS	Bhimal based	0-15	6.81±0.18	2.74±0.31	35.25±3.9	1.67±0.10
			15-30	6.83±0.14	5.34±1.78	32.89±2.62	1.73±0.12
	ASH	Malta+Bhimal+Oak+ Gmelina	0-15	8.11±0.21	4.41±0.46	49.86±8.35	1.50±0.05
			15-30	8.23±0.11	4.78±0.09	27.33±5.77	1.63±0.04
	AH	Malta based	0-15	6.91±0.12	6.68±2.43	38.00±3.52	1.83±0.14
			15-30	7.00±0.05	8.11±1.82	36.34±13.80	1.99±0.26
1300-1800m	AS	Ficus+Bhimal	0-15	5.76±0.37	5.64±0.78	42.44±5.02	1.54±0.10
			15-30	6.03±0.37	5.64±1.12	30.92±4.55	1.27±0.08
	ASH	Walnut+Malta+ Bhimal+Naspati	0-15	6.75±0.32	4.80±0.81	49.95±3.01	1.45±0.14
			15-30	6.90±0.28	3.64±0.08	33.56±0.47	1.57±0.11
	AH	Malta based	0-15	6.94±0.39	2.32±0.39	32.33±2.33	1.47±0.06
			15-30	7.07±0.74	1.81±0.26	26.56±1.82	1.83±0.23
Above 1800m	AS	Oak based	0-15	6.34±0.15	3.28±1.40	48.87±2.09	1.44±0.23
			15-30	6.26±0.20	3.51±1.04	42.36±3.59	1.67±0.27
	ASH	Oak+Malta+ Peach	0-15	7.29±0.64	11.9±2.55	54.98±11.12	1.55±0.17
			15-30	7.10±0.53	9.23±3.93	34.49±9.30	1.61±0.27
	AH	Apple+Malta	0-15	6.86±0.50	2.84±0.50	34.28±9.73	1.98±0.32
			15-30	6.80±0.44	3.28±0.79	38.96±3.56	1.44±0.23

AS- Agri-silviculture system, AH- Agri-horticulture system and ASH- Agri-silvi-horticulture system

Table 6. Soil organic matter (%), Soil organic carbon (%) and soil carbon stock ($t\ ha^{-1}$) of different agroforestry systems along altitudinal gradient

Altitude	System	Agroforestry Models	Depth	SOM	SOC %	SCS ($t\ ha^{-1}$)
800-1300m	AS	Bhimal based	0-15	0.82±0.60	0.63±0.46	42.75±13.83
			15-30	0.91±0.54	0.7±0.41	36.30±2.42
	ASH	Malta+Bhimal+Oak+Gmelina	0-15	3.42±0.14	2.62±0.12	35.88±7.12
			15-30	3.38±0.19	2.59±0.14	40.78±11.61
	AH	Malta based	0-15	1.97±0.73	1.51±0.56	76.61±8.97
			15-30	1.87±0.05	1.43±0.03	40.71±12.12
1300-1800m	AS	Ficus+Bhimal	0-15	1.25±0.64	0.96±0.49	25.23±16.65
			15-30	1.02±0.09	0.78±0.07	15.01±4.04
	ASH	Walnut+Malta+ Bhimal+Naspati	0-15	2.17±0.67	1.66±0.52	36.65±6.87
			15-30	2.27±0.31	1.74±0.23	38.02±2.57
	AH	Malta based	0-15	2.01±0.67	1.54±0.51	35.41±14.80
			15-30	2.75±0.58	2.11±0.44	60.00±4.78
Above 1800m	AS	Oak based	0-15	2.46±0.46	1.88±0.32	15.95±10.69
			15-30	2.07±0.44	1.59±0.33	15.39±6.91
	ASH	Oak+ Malta+Peach	0-15	2.20±0.67	1.69±0.52	59.33±4.36
			15-30	2.17±0.35	1.66±0.27	69.44±8.07
	AH	Apple+Malta	0-15	3.47±0.30	2.65±0.23	42.54±16.76
			15-30	1.70±0.35	1.30±0.27	38.48±0.78

AS- Agri-ilviculture system, AH- Agri-horticulture system and ASH- Agri-silvi-horticulture system relationship with silt. Clay (%) showed a positive connection (p>0.05) with moisture content (%). The positive relationship between clay and soil moisture may be due to decreased in the size of soil particles as earlier mentioned by Rong (2017). SOM had a perfect positive correlation (p<0.01) with SOC. Xiangrong *et al.* (2022) also found the same results, with SOM positively associated with SOC (p<0.01).

3.7 Principal Component Analysis (PCA)

Based on correlation matrix, Principal component analysis was conducted (Table 6). It reveals the relationship between different variables including, sand, silt, clay, BD, pH, WHC, SOM, SOC and SCS and their sites (Agri-silviculture system, Agri-silvi-horticulture system, Agri-horticulture system at LAAS, LAASH, LAAH: at low altitude, MAAS, MAASH, MAAH at mid-altitude, HAAS, HAASH, HAAH at high altitude, 1; 0–15 surface layer and 2; 15–30 subsurface layer) (Fig. 2). It displayed the loading values of the first two principal components, which indicate the contribution of each variable to the principal components. These two principal components is 58.59% of the variance (33.63% from PC1 and 24.96% from PC2). The two principal components with eigenvalues more than 1 were selected, according to method given by Kaiser (1960). The analysis helps identify patterns and interrelationships among the soil properties, highlighting the most influential variables in the dataset. PC1 (33.63%) is mainly associated with sand, silt, SOC %, and SOM, with clay having a substantial negative contribution. Soils that are sandy or have higher organic carbon content have higher scores on PC1. So, PC1 represents a general soil texture and organic matter component, with sand and organic content being the key contributors. PC2 (24.96%) is influenced by pH, SOC%, SOM, and clay, positively correlated to clay and SOC%. This suggests that PC2 represents a component related to soil acidity, organic carbon content, and soil structure (with clay contributing positively).

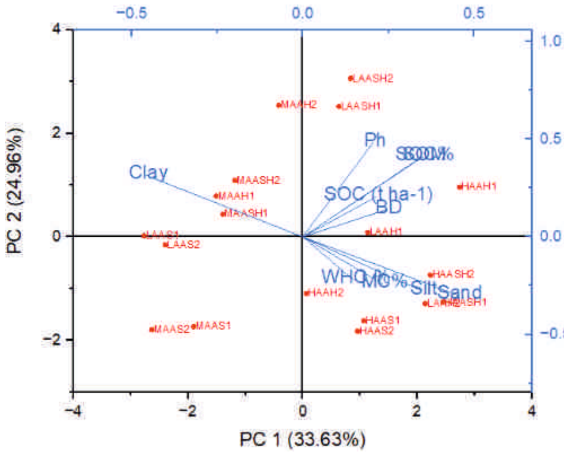

Fig. 2: Principal Component Analysis of different soil parameters along altitudinal gradient and agroforestry systems. ((Agri+silvi, Agri+silvi+horti, Agri+horti at LAAS, LAASH, LAAH: at low altitude, MAAS, MAASH, MAAH at mid altitude, HAAS, HAASH, HAAH at high altitude, 1: 0–15 topsoil and 2: 15–30 subsoil).

4. CONCLUSION

It should be encouraged in voluntary and compliant carbon markets, as it often provides significant additional benefits for local ecosystems and biodiversity. These results indicated that the soil in agroforestry systems at subtropical to temperate altitude regions between clay, sandy clay, and sandy clay loam class is acidic to alkaline in nature. Due to multi-strata, canopy systems like Agri-Silvi-Horticulture systems perform best across all altitudes, demonstrating superior moisture retention and lower bulk density (BD). Therefore, these systems can be considered effective in in maintaining higher water holding capacity WHC (%) and moisture content, making them the most efficient for moisture

Table 7. Pearson correlation analysis between soil physiochemical properties

	MC (%)	Sand (%)	Silt (%)	Clay (%)	SOC (t ha^{-1})	BD (g/cm^3)	WHC (%)	PH	SOC (%)	SOM (%)
MC (%)	1	-	-	-	-	-	-	-	-	-
Sand (%)	-0.444	1	-	-	-	-	-	-	-	-
Silt (%)	0.112	0.631**	1	-	-	-	-	-	-	-
Clay (%)	0.502*	-0.981**	-0.768**	1	-	-	-	-	-	-
SOC(t ha^{-1})	0.413	0.240	-0.222	-0.144	1	-	-	-	-	-
BD(g/cm^3)	0.034	0.163	0.386	-0.231	0.461	1	-	-	-	-
WHC (%)	0.35	0.321	0.115	-0.293	-0.135	-0.303	1	-	-	-
PH	0.122	-0.059	-0.172	0.090	0.456	0.194	-0.061	1	-	-
SOC (%)	-0.130	0.228	0.177	-0.230	0.187	0.231	0.091	0.642**	1	-
SOM (%)	-0.139	0.220	0.179	-0.224	0.177	0.231	0.093	0.639**	1.000**	1

MC (%) =Moisture content, SOC (%) = Soil organic carbon, SOC (t ha^{-1}) = Soil organic stock, WHC= Water holding capacity, SOM (%) = Soil organic matter. *Significant at p > 0.05, **significant at p < 0.01.

management under rainfed conditions in hill agroforestry. The SCS is also the greatest in the Agri-Silvi-Horticulture system at high altitudes. It concluded that Malta + Bhimal + Oak + Gmelina at low Malta + Bhimal + Oak + Gmelina at mid and Oak+ Malta+Peach at high altitude had a good performance. These findings emphasize the impact of altitude and land management practices on soil properties, carbon dynamics, and organic matter content. Agri-Silvi-Horticulture (homegardens) has become a significant area of interest for soil science researchers and agroforesters, particularly in studying the diverse combinations of tree species that can enhance soil fertility and agricultural practices in the Himalayan region. The findings could be crucial in choosing appropriate land use systems and agriculture crops. The new agroforestry model should be investigated further in future studies to better understand its potential and effectiveness. However, a limitation of the study is that the influence of these factors on vegetation remains underexplored, suggesting the need for further research in the future to better understand their impact.

REFERENCES

Bardelli, T., Gómez-Brandón, M., Ascher-Jenull, J., Fornasier, F., Arfaioli, P., and Francioli, D. 2017. Effects of slope exposure on soil physico-chemical and microbiological properties along an altitudinal climosequence in the Italian Alps. *Sci. Total Environ.* 575: 1041–1055.

Bargali, K. and Bargali, S.S. 2020. Effect of size and altitude on soil organic carbon stock in homegarden agroforestry system in Central Himalaya, India. *Acta Ecologica Sinica*, 40(6): 483-491.

Bargali, K., Manral, V., Padalia, K., Bargali, S.S., and Upadhyay, V.P. 2018. Effect of vegetation type and season on microbial biomass carbon in Central Himalayan forest soils, India. *Catena*, 171(12): 125-135.

Budiman Minasny, Alex B, McBratney, Alexandre M.J.-C. 2020. Wadoux Erwin Nyak Akoeb, Tengku Sabrina, Precocious 19th century soil carbon science, *Geoderma Regional*. 22:e00306.

Charan, G., Bharti, V., Jadhav, S., Kumar, S., Angchok, D., Acharya, S., Kumar, P. and Srivastava, R.B. 2012. Altitudinal variations in carbon storage and distribution patterns in cold desert high altitude region of India. *African journal of agricultural research*. 7: 6313-6319.

Dahiya, G., Bhardwaj, K.K., Ahlawat, I., Dhillon, R., Singh, C. and Verma. S. 2022. Soil physical properties as influenced by different agroforestry systems in Haryana. *Ecology, Environment and Conservation*, 28 (2): 984-988.

Dar, J.A. and Somaiah, S. 2015. Altitudinal variation of soil organic carbon stocks in temperate forests of Kashmir Himalayas, India. *Environmental Monitoring and Assessment*,187(2): 11.

FAO. 2009. Enabling agriculture to contribute to climate change mitigation. The Food and Agriculture Organization of the United Nations, Rome, FAO submission to the UNFCCC.

Garcia-Gomez, A., Bernal, M. and Roig, A. 2002. Growth of ornamental plants in two composts prepared from agroindustrial wastes. *Bioresource technology*. 83: 81-7.

Hamid, M., Khuroo, A. A., Malik, A. H., Ahmad, R., and Singh, C. P. 2020. Elevation and aspect determine the differences in soil properties and plant species diversity on Himalayan Mountain summits. *Ecol. Res.* 36: 340–352.

Hu, S., Hu, X., He, L., and Chen, W. 2019. A new material balance equation for dual-porosity media shale gas reservoir. *Energy Procedia*, 158: 5994-6002.

International Organization for Standardization (ISO). ISO 11272-2017. Soil Quality Determination of Dry Bulk Density. International Organization for Standardization, Geneva.

Jackson, M.L. 1973. Soil chemical analysis (2 edition). Prentice Hall of India. Private Limited, New York Delhi pp. 1-498

Kaiser, H. F. 1960. The application of electronic computers to factor analysis. *Educational and Psychological Measurement,* 20: 141–151.

Kamal, A., Mian, I., Akbar, W., Rahim, H., Irfan, M., Ali, S., Alrefaei, A. and Zaman, W. 2023. Effects of soil depth and altitude on soil texture and soil quality index. *Applied Ecology and Environmental Research*. 21: 4135-4154.

Lv, X., Jia, G., Yu, X., and Niu, L. 2022. Vegetation and Topographic Factors Affecting SOM, SOC, and N Contents in a Mountainous Watershed in North China. *Forests*, 13(5), Article 5.

Maqbool, M., Rasool, R. and Ramzan, S. 2017. Soil physicochemical properties as impacted by different land use systems in district Ganderbal, Jammu and Kashmir, India. *International Journal of Chemical Studies* 5(4): 832-840.

Matano, A., Kanangire, C., Anyona, D. , Abuom, P. , Gelder, F. , Dida, G. , Owuor, P. and Ofulla, A. 2015. Effects of Land Use Change on Land Degradation Reflected by Soil Properties along Mara River, Kenya and Tanzania. *Open Journal of Soil Science*, 5: 20-38.

Mayer, S., Wiesmeier, M., Sakamoto, E., Hübner, R., Cardinael, R., Kühnel, A. amd Kögel-Knabner, I. 2022. Soil organic carbon sequestration in temperate agroforestry systems – A meta-analysis. *Agriculture, Ecosystems & Environment*, 323: 107689.

Nizam, M. S., Norziana, J., Sahibin, A. R., and Latiff, A. 2006. Edaphic relationships among tree species in the National Park at Merapoh, Pahang, Malaysia. *Journal of Bioscience*, 17(2): 37-53.

Pearson, T.R. 2007. Measurement guidelines for the sequestration of forest carbon. Vol. 18. US Department of Agriculture, Forest Service, Northern Research Station.

Pinho, R.C., Alfaia S.S., Miller, R.P., Uguen, K., Magalhaes, L.D., Ayres, M., Freitas, V. and Trancoso, R. 2010. Islands of fertility:Soil improvement under indigenous homegardens in the savannas of Roraima, Brazil. *Agrofor. Syst*. 81: 235-247.

Rong, Li & Xingwu, Duan & Feng, Detai & Zhang, Guangli. (2017). Soil Moisture Variation in a Farmed Dry-Hot Valley Catchment Evaluated by a Redundancy Analysis Approach. *Water*. 9: 92.

Sahoo, U. 2020. Variations in soil physico-chemical proper-ties of different traditional homegardens of Mizoram, Northeast India. *Biodiversity in Tropical Ecosystems*, 359-373.

Salve, A., Bhardwaj, D. R., & Tahkur, C. L. 2018. Soil Nutrient study in different agroforestry systems in north western Himalayas. *Bulletin of Environment, Pharmacology and Life Sciences,* 7(2): 63-72.

Semere, M., Cherinet, A., and Gebreyesus, M. 2022. Climate resilient traditional agroforestry systems in Silite district, southern Ethiopia. *J. For. Sci*. 68: 136–144.

Simon, A., Dhendup, K., Rai, P. B., and Gratzer, G. 2018. Soil carbon stocks along elevational gradients in Eastern Himalayan Mountain forests. *Geoder. Reg.* 12: 28–38.

Singh, H., P. Pathak, Kumar, M. and Reghubanshi, S.A. 2011. Carbon sequestration potential of Indo-Gangetic agroecosystem soils. *Trop. Ecol*., 2: 23-28.

Singh, J., Singh, B. and Sharma, S. 2021. Comparison of soil carbon and nitrogen pools among poplar and Eucalyptus-based agroforestry systems in Punjab, India. *Carbon Management.* 12(6): 693-708.

Sundqvist, M. K., Sanders, N. J., and Wardle, D. A. 2013. Community and ecosystem responses to elevational gradients: Processes, mechanisms, and insights for global change. *Annu. Rev. Ecol. Evol. Syst*. 44: 261–280.

Trujillo-González, J. M., Torres-Mora, M. A., Ballesta, R. J., and Brevik, E. C. 2022. Spatial variability of the physicochemical properties of acidic soils along an altitudinal gradient in Colombia. *Environ. Earth Sci*. 81: 108.

Upreti B. 2019. Analysis of soil physical properties of different land forms in and around Nagal Hatnala region, Dehradun. 3: 34-38.

USDA. 2017. Soil survey manual. Soil Survey Division Staff; Soil Conservation Service Volume Handbook 18, U.S. Department of Agriculture.

Verma, T., Bhardwaj, D.R., Sharma, U., Sharma, P., Kumar, D. and Kumar, A., Kumar, A. 2023. Agroforestry systems in the mid-hills of the north-western Himalaya: A sustainable pathway to improved soil health and climate resilience. *Journal of Environmental Management*, 348: 119264.

Vikrant, K., Chauhan, D.S. and Rizvi, R. 2024. Soil Organic Carbon in Agroforestry Systems in Different Altitudes of Tehri District, Uttarakhand, India. *Indian Forester*. 150:99-105.

Walkley and Black, I.A. 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the Chromic Acid titration method. *Soil Science*, 37: 29-37.

Zhang, Y., Ai, J., Sun, Q., Li, Z., Hou, L., Song, L., Tang, G. ... Shao, G. 2021. Soil organic carbon and total nitrogen stocks as affected by vegetation types and altitude across the mountainous regions in the Yunnan Province, south-western China. *CATENA*, 196: 104872.