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Soil Physico-chemical Responses to Integrated Nutrient Management in Lentil Intercropped with Bhimal (*Grewia optiva*) in Agroforestry vs. Open Systems

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The growing concern over health risks associated with the heavy use of chemical fertilizers and pesticides in India, which have been linked to rising cancer cases, underscores the need for sustainable agricultural practices. Integrated Nutrient Management offers a promising solution to enhance soil fertility and support crop health, especially for lentil cultivation within agroforestry systems. This study, conducted at Dr. Y. S. Parmar University of Horticulture and Forestry in Nauni, Solan, Himachal Pradesh, examined the effects of INM on the soil's physical and chemical properties when lentils were intercropped within a *Grewia optiva* (Bhimal) agroforestry system in the mid-hills region of Himachal Pradesh. The experiment evaluated various combinations of organic and inorganic fertilizers, including T1: Recommended Dose of Fertilizer, T2: Farmyard Manure, T3: Vermicompost, T4: Goat Manure, T5: 50% Recommended dose of fertilizer + 50% Farm yard manure, T6: 50% Recommended dose of fertilizer + 50% Vermicompost, T7: 50% Recommended dose of fertilizer + 50% Goat Manure, and T8: Control. These treatments were applied in plots both under the Bhimal-based agroforestry system (S1) and in open field conditions (S2), with three replications per treatment following a factorial randomized block design. Key physical parameters such as bulk density, particle density, porosity, and soil moisture were measured alongside chemical properties, including soil pH, electrical conductivity, organic carbon content, and the availability of nitrogen, phosphorus, and potassium. Data collected over two years was analyzed using R Statistical Software, revealing that INM significantly improved soil properties in the agroforestry system compared to the control. Notably, 100% FYM emerged as the most effective treatment, enhancing soil porosity, moisture, pH, and nutrient availability (N, P, and K). Improvements in soil structure and nutrient levels were particularly evident in the second year, positively impacting lentil growth and yield. The study highlights the potential of INM to promote sustainable, chemical-free agriculture in hilly areas, offering valuable recommendations for farmers and policymakers focused on sustainable agriculture. Specifically, 100% FYM is recommended for improving soil health and crop productivity in the mid-hill region of Himachal Pradesh, providing a model for similar agro-ecological zones aiming to reduce chemical inputs and support human health.

Keywords: Agroforestry; intercropping; Integrated Nutrient Management (INM); FYM; soil fertility.

1. INTRODUCTION

Cancer rates in India have exceeded global averages, leading to its alarming designation as the "cancer capital of the world." This increase is partly attributed to health risks associated with nitrate exposure from extensive chemical fertilizer use in agriculture. Elevated nitrate levels in the soil can contribute to conditions like methemoglobinemia and are linked to various cancers (Picetti et al., 2022). Additionally, pesticide residues in food and water have been linked to numerous health problems, including tumors, skin issues, DNA and cellular damage, immune suppression, and even generational impacts (Pathak et al., 2022). The extensive use of chemical fertilizers and pesticides has also degraded soil health and reduced fertility (Pahalvi et al., 2021). To counter these issues, there is a critical need to implement Integrated Nutrient Management (INM) and agroforestry practices in India. Many farmers heavily depend on chemical fertilizers to increase yields, often overlooking the consequences for soil health. Combining organic inputs, such as farmyard manure and vermicompost, with inorganic fertilizers is essential to restoring soil vitality. This combination aids in transforming nutrients into more accessible forms, promoting efficient crop uptake compared to solely using chemical fertilizers (Wu & Ma, 2015). By integrating organic materials, farmers can reduce reliance on costly chemical inputs, thereby lowering long-term soil pollution risks and promoting sustainable agricultural practices.

Since the early days of agriculture, agroforestry has been valued as an effective land management strategy, known for improving soil quality and conserving water resources (Brown et al., 2018). It supports soil organic carbon enrichment through leaf litter, increases land productivity, reduces soil erosion, and promotes biodiversity, offering farmer's diversified income streams (Dhaka et al., 2020). Furthermore, agroforestry is essential for environmental conservation and soil resource replenishment, both critical for maintaining agricultural productivity in the long term.

Lentil (*Lens culinaris*), a member of the Fabaceae family, is widely used in soups and stews, with its foliage sometimes serving as animal fodder. Known for their high protein content, dietary fiber, B vitamins, iron, and phosphorus, lentils are a highly nutritious legume and one of humanity's earliest food sources (Alexander et al., 2024). As global food demand rises, especially for protein-rich pulses like lentils, it becomes increasingly important to incorporate lentils into diverse cropping systems to boost agricultural output (Gurusamy et al., 2022). Lentils are particularly valued for their resilience in adverse climates and their ability to enhance soil fertility through atmospheric nitrogen fixation (Ramírez & Cantero, 2024).

Integrated Nutrient Management (INM) is a comprehensive strategy designed to boost lentil crop productivity and sustainability in India by effectively balancing organic inputs (such as vermicompost, farmyard manure, compost, and bio-stimulants) with inorganic fertilizers, including essential macro- and micronutrients (Kaur et al., 2024). The rice-lentil crop rotation, particularly significant in the Indo-Gangetic Plains (IGP) of India, plays a vital role in supporting food security in the region. Studies by Nayak et al. (2012) demonstrate that various INM practices contribute positively to soil organic carbon (SOC) stocks and their fractions, thereby enhancing carbon sequestration potential and sustainability within rice-lentil systems. Using NPK fertilizers—whether solely inorganic or combined with organic inputs like farmyard manure, green manure, or crop residues—has been shown to increase concentrations of SOC, particulate organic carbon (POC), and microbial biomass carbon (MBC), along with their sequestration rates (Chaudhary et al., 2017).

The Bhimal tree (*Grewia optiva*) from the Tiliaceae family is widely valued in agroforestry across the Western Himalayas for its high-quality fodder (Kar et al., 2019). This modest-sized tree, reaching up to 15 meters, thrives in subtropical climates at elevations from 150 to 2,500 meters. Known for its versatility, Bhimal is often planted along bunds, terrace edges, and slopes. Its green leaves and young branches provide excellent fodder, while its fruits are edible. The bark yields fibers used in rope-making, and its branches serve various purposes in crafting tools and household items. Traditionally, the green bark has been used for hair washing. Listed as Least Concern on the IUCN Red List (IUCN, 2022), Bhimal is integral to mid-hill agroforestry in Himachal Pradesh, where it supports agri-silviculture systems.

In sustainable agriculture, the use of organic resources—such as farmyard manure (FYM), vermicompost, goat manure, and poultry manure—has become crucial for reducing the harmful impacts associated with excessive reliance on inorganic fertilizers. Prolonged and suboptimal use of chemical fertilizers has shown to degrade soil structure, harm the environment, and impact plant and animal health. Over time, such practices can lead to environmental pollution, reduced soil health, and stagnating crop yields (Mahajan & Gupta, 2009). Therefore, balanced application of both organic and inorganic fertilizers is essential to optimize soil and crop benefits while minimizing negative impacts. This study investigates how Integrated Nutrient Management (INM) affects the physical and chemical properties of soil in lentil intercrops grown within a Bhimal-based agroforestry system in the mid-hill region of Himachal Pradesh.

2. MATERIALS AND METHODS

2.1 Experimental Site

This field experiment was conducted during 2021-2023 at the Experimental Farm of the Department of Silviculture and Agroforestry, Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.), within a 19-year-old *Grewia optiva* agroforestry model. Situated at latitude of 30º 51' N, longitude of 76º 11' E, and an elevation of 1200 meters, the site falls within the subtropical, sub-humid agro-climatic zone of Himachal Pradesh, receiving an annual rainfall between 1000 and 1400 mm. The farm's soil is classified under the Typic Eutrochrept subgroup according to the USDA soil taxonomy.

2.2 Details of Structural Components and Treatments

Rows of Bhimal (*Grewia optiva*) trees were arranged in an East-West orientation with spacing of 9 m × 3 m, established in July 2012. Lentil (*Lens culinaris*), variety Kota Masoor-2, was cultivated both under the *Grewia* trees and in open plots, each measuring 4 m × 2 m, with plant spacing set at 22 cm × 10 cm. Table 1 provides an overview of the treatments applied in this experiment.

2.3 Collection and Preparation of Soil Samples and Analysis

Random soil samples were collected from each sampling unit at a depth of 0-30 cm using a post-hole soil auger prior to sowing and again at lentil harvest over two consecutive years. The samples were placed in labeled cloth bags and transported to the laboratory, where they were air-dried, thoroughly crushed, and passed through a 2 mm sieve. The processed samples were analyzed for physical soil parameters, including bulk density (g cm^{-3}), particle density (g cm^{-3}), porosity (%), and soil moisture (%), using standard procedures. Chemical soil properties—such as pH, electrical conductivity (EC in dS m^{-1}), organic carbon content (%), and available nitrogen, phosphorus, and potassium (kg ha^{-1})—were also assessed. Soil pH was measured using a digital pH meter in a 1:2 soil-to-water suspension, following the method of Jackson (1973). EC was similarly measured using an electrical conductivity meter with a 1:2 soil-to-water suspension (Jackson, 1973). Soil organic carbon (%) was determined by the rapid titration method (Walkley & Black, 1934). Available nitrogen was assessed using Subbiah and Asija's method (1956), phosphorus was analyzed following Olsen et al. (1954) and potassium was estimated by the Merwin and Peech method (1951).

2.4 Initial Soil Properties of the Site

The soil physical and chemical properties of the experimental field estimated before start of the field trial is given in the Table 2.

2.5 Statistical Analysis

The field experiment was designed in factorial Randomized Block Design (RBD) in three replications with eight treatment combinations. The entire data of present study were statistically analyzed by using analysis of variance (ANOVA) in R Statistical Software (version 3.4.0)and treatment means were compared by using critical difference tests at 5% of probability in accordance with the procedure described by Gomez & Gomez (1984).

Table 1. Details of INM treatments applied in the present experiment

Treatments	Details
T_1	RDF (Recommended Dose of Fertilizer)
T_2	FYM (Farm Yard Manure)
T_3	VC (Vermicompost)
T_4	GM (Goat Manure)
T_5	50% RDF + 50% FYM
T_6	50% RDF + 50% VC
T_7	50% RDF + 50% GM
T_8	Control

Table 2. Initial soil physical and chemical properties of the experimental field before sowing

Sr. No.	Parameters	Under Bhimal (S1)	Open Condition (S2)
1	Bulk Density (g cm^{-3})	1.35	1.39
2	Particle Density (g cm^{-3})	2.65	2.77
3	Porosity (%)	50.77	50.13
4	Soil Moisture (%)	7.72	6.93
5	EC soil (dS m^{-1})	0.191	0.178
6	Soil pH	6.76	6.41
7	Organic Carbon (%)	1.18	1.05
8	Available Nitrogen (kg ha^{-1})	250.20	221.47
9	Available Phosphorus (kg ha^{-1})	34.29	32.12
10	Available Potassium (kg ha^{-1})	267.11	234.51

Where, S1: Under Grewia optiva based agroforestry system and S2: Open condition

3. RESULTS AND DISCUSSION

3.1 Physical Properties of Soil in Lentil + Bhimal Based Agroforestry Systems after Harvesting of Lentil

The analyzed result of physical soil parameters *viz.*, bulk Density (g cm^{-3}), particle density (g cm^{-3}), porosity (%) and soil moisture (%) has been presented and discussed in the following way:

3.1.1 Bulk density (g cm^{-3})

The data presented in Table 3 showed a significant effect of planting conditions and integrated nutrient management (INM) on the bulk density (g cm^{-3}) of soil after harvesting of lentil crop under Bhimal based agroforestry systems. In 2022 and 2023, the higher bulk density was observed by S2 (open condition) as compared to S1 (under *Grewia optiva* based agroforestry systems). Among different doses of organic and inorganic fertilizers, the maximum bulk density (1.36 gcm^{-3}) was recorded in T_8 (control), and the minimum (1.22 g cm^{-3}) was recorded in T_2 (100% FYM) in 2022. The maximum bulk density at (1.38 g cm^{-3}) was observed in T_8 (control) whereas, the minimum bulk density (1.24 cm^{-3}) was recorded in T_2 (100% FYM) in 2023. The combined effect of planting conditions and treatment (S×T) showed the non-significant effect on the bulk density. Similar trends were also found in pooled data analysis. The combined data showed that year wise and various interactions found to be non-significant effect on the bulk density of soil.

The two study years revealed that planting conditions and integrated nutrient management significantly influenced soil bulk density. In open conditions, bulk density values were higher, while lower values were observed under the shade of *Grewia optiva* trees. This difference can be attributed to the organic matter accumulation from leaf litter, twigs, and tree roots under tree canopies, which helps reduce soil bulk density. The tree canopy actively contributes organic material to the soil, enhancing soil fertility and structure by lowering bulk density.

These findings align with previous studies. Lodh (2023) reported that soils in *Grewia*-based agroforestry systems had lower bulk density compared to open areas. Similarly, Dash (2020) found that soil bulk density decreased under Poplar trees, in contrast to higher densities in open conditions. Ghosh et al. (2020) documented similar results, noting reduced soil bulk density beneath tree canopies compared to monoculture cropping.

Moreover, the study showed that soil bulk density decreased with the application of 100% FYM compared to control (no manure). This reduction is likely due to increased pore space, better soil aeration, and higher organic carbon content, which together improve soil porosity and water-holding capacity. This research highlights that adding organic matter (such as manure, compost, and biochar) enhances soil structure and porosity, thus lowering bulk density. Prasad et al. (2023) and Garima & Pant (2017) also found that bulk densities were higher in open, unamended soils and lower under integrated nutrient management and organic manure use. Likewise, Bhatt et al. (2019) observed that manure application effectively reduced soil bulk density.

3.1.2 Particle density (g cm^{-3})

The data in Table 4 demonstrate the impact of planting conditions and integrated nutrient management (INM) on soil particle density (g cm^{-3}) following the harvesting of lentils (*Lens culinaris*) under *Grewia optiva* agroforestry (S1) and in open conditions (S2) over two years (2022 and 2023).

Across treatments, particle density was generally higher under open conditions (S2) compared to *Grewia optiva*-based agroforestry (S1). For instance, the pooled means were 2.73 g cm^{-3} in S2 and 2.69 g cm^{-3} in S1, suggesting that *Grewia* canopy cover contributes to slight reductions in particle density. This decrease under the canopy is likely due to the organic matter added by leaf litter and root biomass, which can enhance soil aggregation and structure, ultimately reducing particle density.

Among the treatments, T8 (control) consistently recorded the highest particle density in both systems and years, with pooled means of 2.85 g cm^{-3} in S2 and 2.79 g cm^{-3} in S1. Conversely, T2 (farmyard manure, FYM) had the lowest particle density (pooled means of 2.63 g cm^{-3} in S2 and 2.61 g cm^{-3} in S1), indicating that organic amendments like FYM contribute to reduced particle density, likely due to enhanced soil porosity and aggregation.

Table 3. Effect of planting conditions and integrated nutrient management (INM) on the bulk density (g cm^{-3}) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	1.27	1.31	**1.29**	1.29	1.34	**1.32**	1.28	1.33	**1.30**
T_2	1.20	1.24	**1.22**	1.22	1.26	**1.24**	1.21	1.25	**1.23**
T_3	1.21	1.26	**1.24**	1.24	1.28	**1.26**	1.23	1.27	**1.25**
T_4	1.26	1.30	**1.28**	1.28	1.32	**1.30**	1.27	1.31	**1.29**
T_5	1.24	1.29	**1.26**	1.26	1.31	**1.29**	1.25	1.30	**1.28**
T_6	1.22	1.28	**1.25**	1.24	1.30	**1.27**	1.23	1.29	**1.26**
T_7	1.30	1.34	**1.32**	1.32	1.36	**1.34**	1.31	1.35	**1.33**
T_8	1.33	1.39	**1.36**	1.35	1.41	**1.38**	1.34	1.40	**1.37**
Mean	**1.25**	**1.30**	**1.28**	**1.28**	**1.32**	**1.30**	**1.26**	**1.31**	
$CD_{0.05}$	**S**	**0.01**		**S**	**0.01**		**Y**	**0.01**	
							S	**0.01**	
	T	**0.02**		**T**	**0.02**		**T**	**0.01**	
							Y×S	**NS**	
	S×T	**NS**		**S×T**	**NS**		**Y×T**	**NS**	
							S×T	**NS**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

Table 4. Effect of planting conditions and integrated nutrient management (INM) on the particle density (g cm^{-3}) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	2.78	2.80	**2.79**	2.72	2.79	**2.76**	2.75	2.80	**2.77**
T_2	2.64	2.64	**2.64**	2.59	2.61	**2.60**	2.61	2.63	**2.62**
T_3	2.65	2.68	**2.67**	2.60	2.62	**2.61**	2.62	2.65	**2.64**
T_4	2.70	2.70	**2.70**	2.64	2.65	**2.64**	2.67	2.68	**2.67**
T_5	2.72	2.74	**2.73**	2.67	2.70	**2.68**	2.69	2.72	**2.71**
T_6	2.74	2.76	**2.75**	2.68	2.72	**2.70**	2.71	2.74	**2.72**
T_7	2.73	2.79	**2.76**	2.69	2.74	**2.71**	2.71	2.76	**2.74**
T_8	2.82	2.85	**2.84**	2.76	2.84	**2.80**	2.79	2.85	**2.82**
Mean	**2.72**	**2.75**	**2.73**	**2.67**	**2.71**	**2.69**	**2.69**	**2.73**	
$CD_{0.05}$	**S**	**0.02**		**S**	**0.03**		**Y**	**0.02**	
							S	**0.02**	
	T	**0.04**		**T**	**0.07**		**T**	**0.05**	
							Y×S	**NS**	
	S×T	**NS**		**S×T**	**NS**		**Y×T**	**NS**	
							S×T	**NS**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

Comparing treatments, the integration of organic and inorganic fertilizers (T5: 50% RDF + 50% FYM; T6: 50% RDF + 50% VC; T7: 50% RDF + 50% GM) generally resulted in intermediate particle density values. For example, T5 showed a pooled mean of 2.72 g cm^{-3} in S2 and 2.69 g cm^{-3} in S1, highlighting that combining organic and inorganic nutrients can positively impact soil structure, though to a lesser extent than organic amendments alone.

Statistical analysis revealed that the effects of systems (S), treatments (T), and year (Y) on particle density were significant at the 0.05 level, with critical differences (CD) for each factor. However, interaction effects among these factors (e.g., System × Treatment, Year × System × Treatment) were not significant, suggesting that the main effects of planting conditions, nutrient treatments, and study year consistently influenced particle density without notable combined effects.

These findings align with previous studies as of Tandel et al. (2009), Abiven et al. (2008), Das et al. (2023) and Goldan et al. (2023) who showed that organic amendments lower soil particle density by improving soil organic matter content, which enhances soil structure. For instance, T2 (FYM) demonstrated the lowest density, indicating that FYM increases soil organic carbon, thereby improving soil texture and porosity. Similarly, integrated nutrient management (INM) treatments (T5, T6, T7) offered moderate benefits, highlighting the role of combining organic and inorganic inputs to support soil health.

In conclusion, this study emphasizes the importance of INM in enhancing soil properties within agroforestry systems. Under *Grewia* canopy, organic inputs such as FYM and vermicompost effectively reduced soil particle density, supporting better soil structure and fertility. These findings indicate that using INM in agroforestry systems can optimize soil health, which is essential for sustainable crop production.

3.1.3 Porosity (%)

The planting condition, integrated fertilizer treatments and cultivation in two years recorded significant effects on soil porosity (%) after harvesting of lentil (Table 5). During the first year, second year and pooled data, soil porosity was reported to be higher by S1 (under *Grewia optiva* based agroforestry systems) as compared to S2 (open condition). Regarding the effect of fertilizer treatments, porosity was observed the highest by treatment T2 (100% FYM), whereas the lowest porosity of soil was observed by treatment T8 (control) in all the data sets. In the pooled data, different interactions between year and planting conditions (Y×S), year and treatments (Y×T), planting conditions and treatments (S×T) and year, planting condition and treatments (Y×S×T) were found to be non-significant for the soil porosity after harvest of lentil.

The soil porosity data presented in Table 5 demonstrated significant effects under both integrated nutrient management and planting conditions. When it came to planting conditions, porosity was shown to be higher under a tree canopy and lowest in open conditions. The percentage of soil volume that remains unoccupied by solid materials is best described by the porosity of the soil. The increase in organic matter under trees may be the cause of the soil increased porosity because it increases the microbial population, which also improves the hydrophobicity of the minerals, which increases inter-mineral cohesion and porosity. Tree roots also improve soil porosity by retaining and allowing more water to permeate the soil. The present results are also consistent with studies carried out by Sharma et al. (2015), Tripathi et al. (2017), Dash (2020) and Bhatia (2020) who reported increased porosity under tree canopies relative to open conditions.

3.1.4 Soil moisture (%)

The perusal of the data presented in Table 6 revealed that planting conditions and organic and inorganic fertilizers had a significant effect on the moisture (%) of soil after harvest of Lentil. The combined effect of treatment and planting conditions showed significant effect on the soil moisture with the maximum (16.76%) moisture content was recorded by S_1T_2 and the minimum (14.30%) by S_1T_8. However, the effect of various interactions between year and planting conditions (Y×S), year and treatments (Y×T), planting conditions and treatments (S×T) and year, planting condition and treatments (Y×S×T) was found to be non-significant for soil moisture after harvest of lentil in the pooled data set. In both the years and pooled data, soil moisture found to be higher by S_1 (under *Grewia optiva* based agroforestry systems) as compared to S_2 (open condition). Among different doses of organic fertilizers, the highest soil moisture (16.69, 16.83 and 16.76 %) was recorded by T_2 (100% FYM) which was significant whereas, the lowest soil moisture (14.16, 14.45 and 14.30%) was observed by T_8 (control) in all the data set.

The two years data revealed that the planting conditions and INM had possessed a significant influence on the soil moisture content following crop harvest. In comparison to open conditions, *Grewia optiva* tree canopy showed the maximum soil moisture among planting conditions. The decrease in evapotranspiration via the tree canopy may also be a cause of this rise in moisture levels in tree-based systems. In addition, the organic matter that trees give to the soil through the decomposition of their leaves improves the moisture content and soil structure. Kumar et al. (2023) also noted that the moisture content beneath *Grewia optiva* trees was higher than when Bhringraj was grown alone. Similar to this, Sarto et al. (2022) also verified that there is more moisture beneath the tree canopy than in the open. Similarly, the data related to the various integrated nutrient treatments showed that T_2 (100% FYM) had the maximum soil moisture content, while T_8 (control) had the lowest. This could be due to the inclusion of organic manure, which has an elevated water retention capacity and can be composted or well-rotted animal dung. The breakdown of organic manures creates a layer of mulch that protects the soil surface. Further, it lowers soil exposure to direct sunlight and reduces the direct influence that wind has on soil surface, this mulch acts as a barrier to reduce evaporative losses. The current results align with research conducted by Jagadeeshwari & Kumaraswamy (2000), Tripathi et al. (2017) and Sharma et al. (2015) all of which saw increased moisture content in their studies when used organic manures or integrated nutrition management, in comparison to control.

3.2 Chemical Properties of Soil in Lentil +Bhimal Based Agroforestry System after Harvesting of Lentil

The physical soil parameters *viz.*, pH, EC (dS m-1), OC (%) and available N, P, and K (kg ha-1) has been presented and discussed in the following way:

3.2.1 Soil pH

The content of the data presented in Table 7 revealed that during both the years and pooled data, both planting conditions and INM showed a non-significant effect on soil pH after harvesting of lentil. The combined effect of planting conditions and treatment (S×T) showed a significant effect on the soil pH the maximum (7.33) in S_2T_1 while the minimum (6.78) in S_1T_4 in the year 2022. Pooled data revealed that year (Y) showed a significant effect on the soil pH the maximum (7.24) in 2023 and the minimum (7.11) in 2022. However, planting conditions (S) and treatment (T) had a non-significant effect on soil pH. The combined interaction effect of year and planting conditions (Y×S), year and treatments (Y×T), planting conditions and treatments (S×T) and year, planting condition and treatments (Y×S×T) was found to be non-significant for effect on soil pH after harvest of lentil.

Table 5. Effect of planting conditions and integrated nutrient management (INM) on Porosity (%) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	**S_2**	**Mean**	**S_1**	**S_2**	**Mean**	**S_1**	**S_2**	**Mean**
T_1	46.98	45.29	**46.14**	48.42	47.24	**47.83**	47.70	46.27	**46.98**
T_2	49.66	47.89	**48.78**	50.70	49.77	**50.23**	50.18	48.83	**49.51**
T_3	46.99	45.75	**46.37**	49.08	47.68	**48.38**	48.04	46.71	**47.37**
T_4	48.01	46.55	**47.28**	49.92	48.52	**49.22**	48.97	47.53	**48.25**
T_5	47.03	45.55	**46.29**	48.62	47.45	**48.03**	47.82	46.50	**47.16**
T_6	46.24	44.63	**45.44**	47.84	46.49	**47.16**	47.04	45.56	**46.30**
T_7	47.99	47.50	**47.75**	49.68	49.22	**49.45**	48.83	48.36	**48.60**
T_8	46.07	45.12	**45.59**	47.06	46.93	**47.00**	46.56	46.03	**46.29**
Mean	**47.37**	**46.04**	**46.70**	**48.91**	**47.91**	**48.41**	**48.14**	**46.97**	
$CD_{0.05}$	**S**	**0.62**		**S**	**0.82**		**Y**	**0.52**	
							S	**0.52**	
	T	**1.24**		**T**	**1.65**		**T**	**1.05**	
							Y×S	**NS**	
	S×T	**NS**		**S×T**	**NS**		**Y×T**	**NS**	
							S×T	**NS**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

Table 6. Effect of planting conditions and integrated nutrient management (INM) on the Soil Moisture (%) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	14.77	14.15	**14.46**	15.07	14.64	**14.86**	14.92	14.40	**14.66**
T_2	16.99	16.39	**16.69**	17.02	16.64	**16.83**	17.01	16.52	**16.76**
T_3	16.94	16.34	**16.64**	16.97	16.57	**16.77**	16.96	16.46	**16.71**
T_4	16.50	15.99	**16.25**	16.74	16.21	**16.47**	16.62	16.10	**16.36**
T_5	16.20	15.21	**15.70**	16.18	15.65	**15.91**	16.19	15.43	**15.81**
T_6	15.62	15.08	**15.35**	15.68	15.22	**15.45**	15.65	15.15	**15.40**
T_7	15.41	14.80	**15.11**	15.59	15.08	**15.33**	15.50	14.94	**15.22**
T_8	14.26	14.06	**14.16**	14.53	14.36	**14.45**	14.40	14.21	**14.30**
Mean	**15.84**	**15.25**	**15.54**	**15.97**	**15.55**	**15.76**	**15.91**	**15.40**	
$CD_{0.05}$	**S**	**0.18**		**S**	**0.05**		**Y**	**NS**	
							S	**NS**	
	T	**0.36**		**T**	**0.10**		**T**	**0.01**	
							Y×S	**NS**	
	S×T	**NS**		**S×T**	**0.14**		**Y×T**	**NS**	
							S×T	**0.02**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

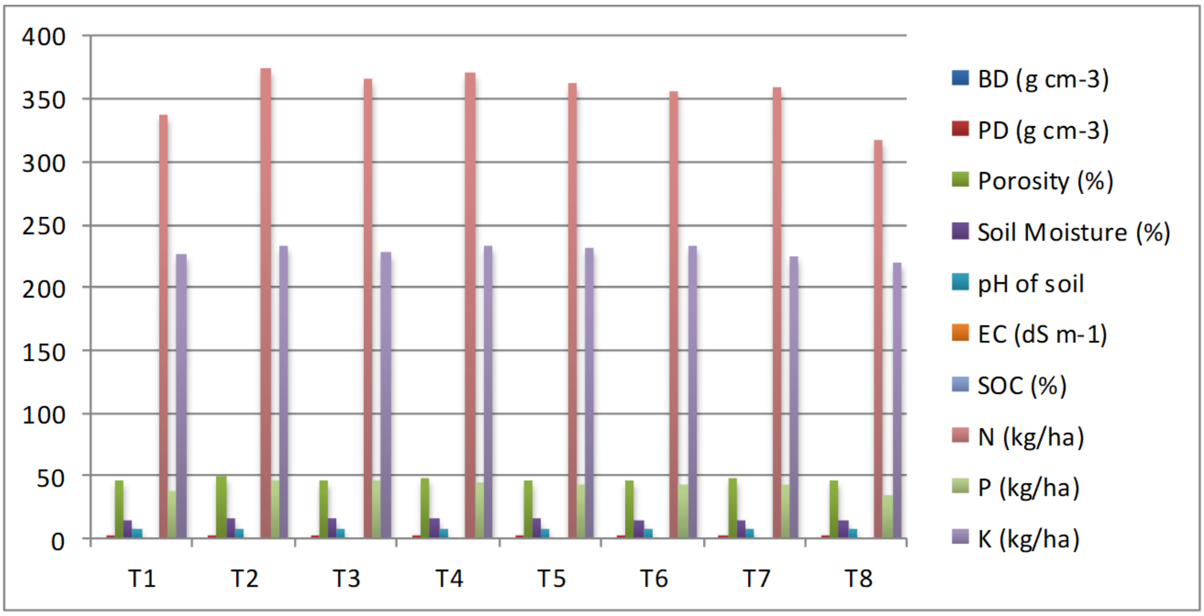

Fig. 1. Overall effect of treatments on different physico-chemical properties of soil

In comparison to open conditions, there was a decrease in soil pH under agroforestry conditions. There are several reasons for the lower pH of the soil beneath tree canopies. This effect is exacerbated by the yearly deposition of leaf litter, which breaks down and emits carbon dioxide (CO_2) and organic acids that lower pH levels in the soil. The metabolic activities of tree roots also emit organic acids, which adds to the acidity of the soil under tree canopy. The results of the current study were also similar to the Dash (2020), Bhatia (2020) who reported lowest values of soil pH under trees based agroforestry system as compared to sole cropping patterns. Conversely, distinct nutrient management strategies also have a significant effect on soil pH. The control had the highest pH, whereas the 100% FYM treatment showed the lowest pH values, which were identical to the pH levels in 100% vermicompost treatment. The organic treatments have caused a decrease in soil pH, which can be ascribed to the acidifying effect of organic acids produced during the breakdown of organic supplement. The intricate relationships between organic additions, microbial activity, and soil pH variations are highlighted by this dual influence. These results are consistent with studies by Mehta (2023) who found that the control plot with no manure had the greatest pH and that the lowest pH was observed with 100% goat dung, which was comparable to the values of pH in the 100% FYM treatment.

Table 7. Effect of planting conditions and integrated nutrient management (INM) on the pH of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	6.94	7.33	**7.14**	6.96	7.16	**7.06**	6.95	7.25	**7.10**
T_2	7.10	7.15	**6.97**	7.05	7.16	**7.10**	7.08	7.16	**7.12**
T_3	7.12	7.13	**7.13**	7.35	7.29	**7.32**	7.24	7.21	**7.22**
T_4	6.78	7.33	**7.06**	7.42	7.17	**7.30**	7.10	7.25	**7.18**
T_5	7.19	6.97	**7.08**	7.09	7.10	**7.10**	7.14	7.04	**7.09**
T_6	7.21	6.84	**7.18**	7.15	7.47	**7.31**	7.18	7.16	**7.17**
T_7	7.20	6.93	**7.07**	7.20	7.45	**7.32**	7.20	7.19	**7.20**
T_8	7.20	7.29	**7.25**	7.51	7.37	**7.44**	7.36	7.33	**7.34**
Mean	**7.09**	**7.12**	**7.11**	**7.22**	**7.27**	**7.24**	**7.15**	**7.20**	
$CD_{0.05}$	**S**	**NS**		**S**	**NS**		**Y**	**0.11**	
							S	**NS**	
	T	**NS**		**T**	**NS**		**T**	**NS**	
							Y×S	**NS**	
	S×T	**0.38**		**S×T**	**NS**		**Y×T**	**NS**	
							S×T	**NS**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

Table 8. Effect of planting conditions and integrated nutrient management (INM) on the electrical Conductivity (dS m^{-1}) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	0.178	0.140	**0.159**	0.133	0.120	**0.127**	0.156	0.130	**0.143**
T_2	0.394	0.294	**0.344**	0.349	0.271	**0.310**	0.371	0.282	**0.327**
T_3	0.246	0.138	**0.192**	0.201	0.118	**0.160**	0.224	0.128	**0.176**
T_4	0.276	0.144	**0.210**	0.231	0.124	**0.178**	0.254	0.134	**0.194**
T_5	0.280	0.166	**0.223**	0.235	0.146	**0.191**	0.258	0.156	**0.207**
T_6	0.298	0.171	**0.235**	0.253	0.151	**0.202**	0.276	0.161	**0.218**
T_7	0.327	0.174	**0.251**	0.282	0.154	**0.218**	0.305	0.164	**0.234**
T_8	0.168	0.128	**0.148**	0.130	0.117	**0.123**	0.149	0.122	**0.136**
Mean	**0.271**	**0.169**	**0.220**	**0.227**	**0.150**	**0.188**	**0.249**	**0.160**	
$CD_{0.05}$	**S**	**NS**		**S**	**NS**		**Y**	**0.002**	
							S	**0.002**	
	T	**NS**		**T**	**NS**		**T**	**0.005**	
							Y×S	**0.003**	
	S×T	**0.01**		**S×T**	**0.01**		**Y×T**	**NS**	
							S×T	**0.007**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

Table 9. Effect of planting conditions and integrated nutrient management (INM) on the soil organic carbon (%) after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	1.48	1.39	**1.44**	1.53	1.43	**1.48**	1.51	1.41	**1.46**
T_2	1.67	1.49	**1.58**	1.72	1.52	**1.62**	1.69	1.50	**1.60**
T_3	1.64	1.47	**1.56**	1.69	1.51	**1.60**	1.67	1.49	**1.58**
T_4	1.49	1.44	**1.46**	1.54	1.47	**1.50**	1.51	1.45	**1.48**
T_5	1.60	1.49	**1.55**	1.65	1.53	**1.59**	1.63	1.51	**1.57**
T_6	1.58	1.44	**1.51**	1.63	1.47	**1.55**	1.60	1.45	**1.53**
T_7	1.47	1.41	**1.44**	1.52	1.44	**1.48**	1.49	1.42	**1.46**
T_8	1.37	1.33	**1.35**	1.42	1.36	**1.39**	1.39	1.34	**1.37**
Mean	**1.54**	**1.43**	**1.48**	**1.59**	**1.47**	**1.53**	**1.56**	**1.45**	
$CD_{0.05}$	**S**	**0.01**		**S**	**0.01**		**Y**	**0.01**	
							S	**0.01**	
	T	**0.02**		**T**	**0.03**		**T**	**0.22**	
							Y×S	**NS**	
	S×T	**0.03**		**S×T**	**0.04**		**Y×T**	**NS**	
							S×T	**0.32**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

3.2.2 EC soil (ds m^{-1})

The critical examinations of the data presented in the Table 8 revealed that both planting conditions and INM showed a significant effect on the EC of soil after harvesting of lentil. The soil EC was recorded higher by S_1 (under *Grewia optiva* based agroforestry systems) as compared to S2 (open condition) in all the data sets. Among different doses of organic and inorganic fertilizers, the maximum soil EC (0.344, 0.310 and 0.327 dS m^{-1}) was recorded by T2 (100% FYM) whereas, the minimum soil EC (0.148, 0.123 and 0.136 dS m-1) was recorded in T8 (control) in all the data sets. Interaction effect of year and planting conditions (Y×S) had a significant effect on soil EC; maximum (0.271 dS/m) soil EC was recorded in Y_1S_1 and minimum (0.150 dS/m) soil EC was recorded in Y_2S_2 and significant effect the interaction combination between the system-planting conditions and treatments (S×T); maximum (0.371 dS/m) soil EC in S_1T_2 FYM -100% N equivalent basis (under *Grewia optiva* based agroforestry systems) whereas, minimum (0.122 dS/m) in S_2T_8 control-no manure (open condition). However, Interaction effect of year and treatment (Y×T), year, planting conditions and treatment (Y×T×S) showed a non-significant effect on the soil EC.

Regarding planting conditions, *Grewia* optiva based agroforestry system produced the highest electrical conductivity whereas, open conditions displayed the lowest. When compared to a single crop, higher electrical conductivity in an agroforestry system may be caused by the buildup and breakdown of leaf litter, which improves the soil basic salt concentration. The breakdown of organic matter releases ions, including salts, into the soil solution, which increases EC. Tree canopies can also intercept and concentrate rainfall, which results in higher concentrations of salts in the soil surrounding the tree base. These findings are supported by Kumar et al. (2023) who reported significantly higher electrical conductivity under *Grewia optiva* trees compared to open conditions. As a result, of the fertilizer treatments, T2 (100% FYM) showed the highest electrical conductivity, while T8 (no manure) exhibited the lowest. The application of nutrient sources was found to boost electrical conductivity, with organic manure registering the highest values among the nutrient sources studied in this study. The presence of soluble ions like potassium (K+), sodium (Na+), calcium (Ca2+), and magnesium (Mg2+) in FYM may be the cause of high EC under FYM. Secondly, FYM decomposes in the soil into simpler forms throughout the decomposition process, releasing ions into the soil solution and raising the EC. As compared to alternative nutrient sources, the application of 100% FYM produced maximum electrical conductivity, which is consistent with the findings of several other researchers like Kaushal et al. (2016) who found that applying organic manure raises the electrical conductivity (EC) of the soil.

3.2.3 Organic carbon (%)

The effect of planting conditions and INM showed a significant effect on organic carbon of soil after harvesting of lentil (Table 9). During both the years as well as pooled data, organic carbon was recorded higher by S_1 (under *Grewia optiva* based agroforestry systems) as compared to S_2 (open condition). Among different doses of organic and inorganic fertilizers, treatment T_2 (100% FYM) resulted in the maximum organic carbon whereas, the minimum was recorded by T_8 (control) in all the data sets. The combined effect of planting conditions and treatment (S×T) showed significant effect on organic carbon of soil with the maximum (1.67%, 1.72% & 1.69%) by S_1T_2 and the minimum (1.33%, 1.36& & 1.33%) by S_2T_8 during both the years as well as in pooled data analysis.

The planting conditions as well as nutrient management had a significant effect on the organic carbon content of the soil. The results unequivocally showed that, in contrast to single cropping, the maximum organic carbon was found beneath of Bhimal trees during planting conditions. The reduced oxidation of organic material in the vicinity of tree shade, the regular contribution of annual litter and the recycling of biomass and root exudates are all responsible for the improved level of organic carbon under the tree canopy. Furthermore, lignified cells can be found in the roots, bark and litter of trees, among other plant parts. The results are in conformity with the findings of Zahoor et al. (2021), who found that agroforestry systems had a higher soil organic carbon content than open conditions. Talking of different fertilizer applications, an advantageous sequestration of soil organic carbon can be attributed to the collaborative relationships among soil organic carbon, boosted microbial life and the enzymes involved in carbon cycling, which resulted in a higher organic carbon content noticed during the organic manure application. In addition, adding organic manure promotes soil health and highlights other advantages too of using organic manure for effective carbon sequestration and long-term soil management. These results are consistent with the study conducted by Mehta (2023), Adeleke et al. (2017), Sharma (2021), Six et al. (2002) which found that 100% goat manure had maximum soil organic carbon content (0.81%) than control plots (0.51%). Moreover, Garima & Pant (2017) found that 100% FYM had more soil organic carbon (15.18 g kg-1) than the control (13.80 g kg^1). Tripathi et al. (2017) observed greater organic carbon content under the organic manures as compared to inorganic and control.

3.2.4 Available nitrogen (kg/ha)

The result of the data presented in Table 10 reflected that both planting conditions and INM showed significant effect on the available nitrogen (kg/ha) of soil after harvest of lentil crop in Rabi Season. In all he years, the maximum available nitrogen was recorded higher by S_1 as compared to S_2 (open condition). Among different doses of organic and inorganic fertilizers, the maximum available nitrogen (372.11, 377.34 and 374.72 kg/ha) was recorded by T_2 (100% FYM) whereas, the minimum (315.38, 320.61 and 317.99 kg/ha) was recorded by T_8 (control) in all the data sets. The combined effect of planting conditions and treatment (S×T) showed significant effect on available nitrogen of soil maximum (385.02, 389.69 and 387.36 kg/ha) S_1T_4 under *Grewia optiva* based agroforestry systems with applied GM (100% N equivalent basis) (307.08, 312.87 and 309.97 kg/ha) in S_2T_8 (open condition) without manure-control during both the years as well as pooled data analysis. However, the effect of various interactions between year and planting conditions (Y×S), year and treatments (Y×T), and year, planting condition and treatments (Y×S×T) was found to be non-significant for effect on available nitrogen (kg/ha) of lentil.

The results revealed that planting conditions and fertilizer application had a significant effect on the soil nitrogen content in both years. The data showed that the agroforestry system comprised of *Grewia optiva* trees accumulates the highest content of available nitrogen than the open condition (sole cropping of field crops). Nitrogen directly influences metabolic processes that impact crop production and yield. Many processes, including quick decomposition of litter, reduction of nitrogen loss via the canopy, enhanced microclimate that reduces leaching and moderate rainfall intensity and regular nitrogen cycling, are responsible for the high nitrogen content underneath the tree crown. Additionally, the direct relationship between the amount of nitrogen in the soil and the organic carbon in the soil implies that higher levels of organic carbon in the soil lead to higher levels of nitrogen, highlighting the interrelated dynamics that affect the availability of nutrients in the soil.

Bisht et al. (2017) reported the highest available nitrogen in agroforestry systems as that of sole cropping systems. The available nitrogen concentration under organic manures (100% FYM/Vermicompost/Goat manure) was higher than under other nutrient treatments. This could be because applying FYM supplies the earth with organic matter, starts a microbial- mediated breakdown process. This helps in humus formation, which acts as a reservoir for nutrients, especially nitrogen. Furthermore, the organic matter found in FYM is essential for reducing nitrogen loss through volatilization and leaching, improving the overall effectiveness of nitrogen uptake by plants. In, nitrogen is released from inorganic fertilizers quickly, which causes losses from the system due to de-nitrification and conversion processes. Consequently, there is less nitrogen available in the soil. The current findings are consistent with the research conducted by Ghosh et al. (2020), Dhaliwal et al. (2023), Han et al. (2016), Bhanwaria et al. (2022) who found that organic manures raised the nitrogen level more than the control (no manure) plot.

3.2.5 Available phosphorus (kg/ha)

Taking, available phosphorus into considerance, it was found highest values were recorded by S_1 (under *Grewia optiva* based agroforestry systems) as compared to S_2 (open condition). Among different doses of organic and inorganic fertilizers, the maximum available phosphorus was recorded by T_2 (100% FYM) whereas, the minimum was recorded by T_8 (control) in all the years. In general, the maximum (44.94 kg/ha) available phosphorus was recorded in the year 2023 in comparison to the year 2022 (41.60 kg/ha). The combined effect of planting conditions and treatment (S×T) showed significant effect on available phosphorus in soil maximum (46.77, 51.21 and 48.99 kg/ha) by S_1T_2 whereas, minimum (31.61, 34.27 and 32.94 kg/ha) in S_2T_8 during both the years as well as polled data. The interactions between year and planting conditions (Y×S) showed significant effect on the available phosphorus in soil maximum (46.44 kg/ha) in Y_2S_1 (39.54 kg/ha) in Y_1S_2. However, the effect of various interactions between year and treatments (Y×T) and year, planting condition and treatments (Y×S×T) was found to be non-significant for effect on available phosphorus (kg/ha) in soil after harvest of lentil.

The result reflected the planting conditions and integrated nutrient management had a significant effect on the available phosphorus content in the soil. It has been noted that agroforestry systems based on *Grewia optiva* produced a higher content of accessible phosphorus than the open conditions. The combination of organic matter decomposition, mycorrhizal associations, effective nutrient cycling, decreased erosion and accumulation of organic matter in agroforestry systems jointly supports a rise in phosphorus levels in the soil, supporting plant growth and overall soil fertility. This may be the cause of the increase in phosphorus content under agroforestry. Furthermore, when organic compounds break down in the soil, organic acids are released. These acids reduce metal ions, chelate with phosphates to form complexes and compete with them for exchange sites, all of which contribute to the enhanced release of phosphorus. The results of this study are also aligned with previous research conducted by Kar et al. (2019) which showed the superiority of agroforestry systems for achieving the ideal phosphorus content. In the present investigation, with respect to different doses of organic and inorganic manures, T2 (100% FYM) had the maximum content of significant effect on phosphorus while, T8 (no manure) had the minimum available phosphorus. The results of this study demonstrated that the application of organic manure treatments mobilized the available soil phosphorus concentration at its peak. This may be increased due to the increase in organic acids that occurs during the breakdown of organic manures, which promotes the proliferation of bacteria and fungi, hence augmenting the soil nutrient availability environment. These results are in harmony with the finding of Kumar et al. (2023), Garima et al. (2017) and Ghosh et al. (2020) who stated that the maximum amount of accessible soil phosphorus content was observed under organic manures as compared to the control (no manure).

3.2.6 Available potassium (kg/ha)

With reference to potassium, it was found that during both the years, the available potassium was recorded higher by S_1 (under *Grewia optiva* based agroforestry systems) as compared to S_2 (open condition). Moreover, among different doses of organic and inorganic fertilizers, the maximum available potassium was recorded by T_2 (100% FYM) whereas, the minimum was recorded by T_8 (control) in all the data sets. In general, the maximum (233.21 kg/ha) available potassium was recorded in the year 2023 in comparison to the year 2022 (225.51 kg/ha). The

Table 10. Effect of planting conditions and integrated nutrient management (INM) on the available nitrogen (kg/ha) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	344.76	326.54	**335.65**	349.43	332.33	**340.88**	347.09	329.43	**338.26**
T_2	370.40	373.81	**372.11**	375.07	379.61	**377.34**	372.73	376.71	**374.72**
T_3	383.61	344.50	**364.06**	388.28	350.30	**369.29**	385.95	347.40	**366.67**
T_4	385.02	350.91	**367.97**	389.69	356.70	**373.20**	387.36	353.81	**370.58**
T_5	374.89	345.81	**360.35**	379.56	351.60	**365.58**	377.23	348.70	**362.97**
T_6	368.17	336.94	**352.55**	372.84	342.73	**357.78**	370.50	339.83	**355.17**
T_7	362.32	349.74	**356.03**	366.99	355.53	**361.26**	364.66	352.64	**358.65**
T_8	323.68	307.08	**315.38**	328.35	312.87	**320.61**	326.01	309.97	**317.99**
Mean	**364.11**	**341.92**	**353.01**	**368.78**	**347.71**	**358.24**	**366.44**	**344.81**	
$CD_{0.05}$	**S**	**3.64**		**S**	**4.32**		**Y**	**2.89**	
							S	**2.89**	
	T	**7.28**		**T**	**8.65**		**T**	**5.78**	
							Y×S	**NS**	
	S×T	**10.29**		**S×T**	**12.24**		**Y×T**	**NS**	
							S×T	**8.18**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

Table 11. Effect of planting conditions and integrated nutrient management (INM) on the available phosphorus (kg/ha) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	37.19	36.49	**36.84**	41.64	39.15	**40.40**	39.42	37.82	**38.62**
T_2	46.77	42.32	**44.54**	51.21	44.98	**48.09**	48.99	43.65	**46.32**
T_3	46.45	41.79	**44.12**	50.89	44.45	**47.67**	48.67	43.12	**45.90**
T_4	44.03	42.89	**43.46**	48.47	45.55	**47.01**	46.25	44.22	**45.24**
T_5	42.99	40.66	**41.82**	47.43	43.32	**45.37**	45.21	41.99	**43.60**
T_6	43.30	39.77	**41.53**	47.74	42.43	**45.08**	45.52	41.10	**43.31**
T_7	41.94	40.77	**41.36**	46.38	43.43	**44.91**	44.16	42.10	**43.13**
T_8	33.26	31.61	**32.44**	37.70	34.27	**35.99**	35.48	32.94	**34.21**
Mean	**41.99**	**39.54**	**40.76**	**46.44**	**42.20**	**44.32**	**44.21**	**40.87**	
$CD_{0.05}$	**S**	**0.33**		**S**	**0.36**		**Y**	**0.30**	
							S	**0.30**	
	T	**0.67**		**T**	**0.72**		**T**	**0.60**	
							Y×S	**0.42**	
	S×T	**0.96**		**S×T**	**1.02**		**Y×T**	**NS**	
							S×T	**0.85**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

Table 12. Effect of planting conditions and integrated nutrient management (INM) on the available potassium (kg/ha) of soil after harvesting of lentil (*Lens culinaris*) under *Grewia optiva* Drummond. based agroforestry system

Systems (S) / Treatments (T)	1st Year (2022)			2nd Year (2023)			Pooled		
	S_1	S_2	Mean	S_1	S_2	Mean	S_1	S_2	Mean
T_1	244.76	202.05	**223.41**	252.87	209.34	**231.11**	248.82	205.70	**227.26**
T_2	242.85	217.19	**230.02**	250.96	224.48	**237.72**	246.90	220.84	**233.87**
T_3	229.05	221.17	**225.11**	237.16	228.46	**232.81**	233.11	224.82	**228.96**
T_4	238.95	221.35	**230.15**	247.05	228.64	**237.85**	243.00	224.99	**234.00**
T_5	237.97	218.67	**228.32**	246.07	225.96	**236.02**	242.02	222.31	**232.17**
T_6	233.87	224.29	**229.08**	241.97	231.58	**236.78**	237.92	227.93	**232.93**
T_7	227.71	214.86	**221.29**	235.82	222.15	**228.99**	231.77	218.51	**225.14**
T_8	222.69	210.81	**216.75**	230.80	218.10	**224.45**	226.74	214.45	**220.60**
Mean	**234.73**	**216.30**	**225.51**	**242.84**	**223.59**	**233.21**	**238.78**	**219.94**	
$CD_{0.05}$	**S**	**0.98**		**S**	**0.99**		**Y**	**0.77**	
							S	**0.77**	
	T	**1.97**		**T**	**1.99**		**T**	**1.54**	
							Y×S	**NS**	
	S×T	**2.79**		**S×T**	**2.82**		**Y×T**	**NS**	
							S×T	**2.18**	
							Y×S×T	**NS**	

Note: *S_1: under Grewia optiva based agroforestry system and S_2: Open conditions*

combined effect of planting conditions and treatment (S×T) showed significant effect on available potassium in soil maximum (244.76, 252.87 and 248.82 kg/ha) under S_1T_1 whereas, the minimum (210.81, 218.10 and 215.45 kg/ha) in S_2T_8 in all data sets. However, the effect of various interactions between year and planting conditions (Y×S), year and treatments (Y×T) and year, planting condition and treatments (Y×S×T) was found to be non-significant for effect on available potassium (kg/ha) in soil after harvest of lentil.

The data of two consecutive years revealed that the soil potassium was significantly influenced by the planting condition and fertilizer sources. The increased potassium concentration beneath the tree canopy can be attributed to the high mineralization and addition of leaf litter, which raises the potassium levels in the soil under the tree cover. Potassium influences the efficiency of photosynthesis, modifies the activity of enzymes, and maintains the skeletal strength of plant membranes. Moreover, potassium optimization is essential for improving the osmotic potential of plants and guarantees general resistance and flexibility to changes in the environment (Garima et al., 2021). Thakur (2023) also reported higher potassium content under agroforestry than the sole cropping system. However, among different manures and fertilizers, the available soil potassium exhibited maximum under pure organic treatments *i.e.*, 100% FYM which was at par with vermicompost and goat manure, while the minimum was recorded in control. The increased potassium content in soils treated with organic manures, especially FYM, can be attributed to several factors. The application of organic manures leads to an increased release of potassium through the gradual decomposition of organic matter. This process is further augmented by the formation of humus, improved microbial activity and the enhanced cation exchange capacity of the soil, collectively contributing to the sharp availability of potassium in the soil. A similar study was also conducted by Ghosh et al. (2020) who reported that integration of organic and inorganic manures increases the potassium content of the soil as compared to RDF alone.

4. CONCLUSION

This study reveals that Bhimal-based agroforestry systems significantly enhance the physical and chemical properties of soil when lentil is intercropped, offering distinct advantages over open cultivation. Over a two-year period, agroforestry practices demonstrated a clear improvement in soil quality by reducing bulk and particle density and pH levels, while increasing porosity, soil moisture, electrical conductivity, organic carbon, and the availability of key nutrients like nitrogen, phosphorus, and potassium. Integrated Nutrient Management (INM), particularly with organic and inorganic fertilizers, proved effective in positively influencing these soil characteristics. Notably, the application of 100% farmyard manure (FYM) led to marked improvements, further reducing bulk density and pH and boosting porosity, moisture, conductivity, organic carbon, and nutrient levels. Soil quality indicators continued to improve in the second year, underscoring the cumulative benefits of INM practices over time. The findings advocate for 100% FYM as a recommended approach for farmers in the hilly regions of Himachal Pradesh, promoting sustainable agriculture and natural farming. This research provides valuable insights for policymakers working to optimize crop productivity while safeguarding soil health in similar agro-ecological zones, thus contributing to improved plant resilience and potential health benefits for communities.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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