



Comparative Analysis of Microbiological Aspects in Forest and Agricultural Soils across Major Soil Orders of Haryana

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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

This study evaluates and compares the microbiological properties of forest and agricultural soils across major soil orders (Inceptisols, Entisols, Aridisols, and Alfisols) in Haryana to assess the impact of land use on soil biological health. Surface soil samples were collected at five representative sites of each soil order, spanning districts including Sirsa, Hisar, Jind, Karnal, Ambala, Mahendergarh, and Bhiwani. Composite soil samples were prepared by mixing three randomly collected auger cores per site, avoiding disturbed or recently fertilized areas. Each sample

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was split: one part air-dried for physico-chemical analysis, the other kept moist for immediate microbiological assessment. Forest soils exhibited 83.78 $\mu\text{gNH}_4\text{-N g h}^{-1}$ higher urease activity vs. 38.36 $\mu\text{gNH}_4\text{-N g h}^{-1}$, 65.25 $\mu\text{g TPF/g/h}$ greater dehydrogenase activity (DHA) vs 27.13 $\mu\text{g TPF/g/h}$, 937.60 $\mu\text{g PNP/g/h}$ maximum alkaline phosphatase (APA) vs. 406.80 $\mu\text{gPNP/g/h}$, higher 383.89 mg kg^{-1} microbial biomass carbon (MBC) vs. 107.33 mg kg^{-1} , and greater 88.82 mg kg^{-1} microbial biomass nitrogen (MBN) vs. 28.32 mg kg^{-1} compared to agricultural systems. Among soil orders, Inceptisols and Alfisols supported more diverse and active microbial communities compared to Aridisols and Entisols, indicating a strong relationship between inherent soil characteristics and microbial functionality. The study concludes that land use type and soil order collectively influence soil microbial dynamics, with forest ecosystems preserving higher microbial vitality. A novel observation in this investigation was the remarkably high enzymatic activity recorded in forest Alfisols, suggesting their exceptional potential for nutrient cycling and soil health preservation. These findings emphasize the need to incorporate soil biological indicators into sustainable land management practices in Haryana's diverse agro-ecological settings.

Keywords: Forest; agricultural; land use; soil orders; MBC; MBN; soil health; sustainable land management.

1. INTRODUCTION

Haryana has a total geographical area of 4.42 million hectares (Mha), with 0.53 Mha under horticultural crops. Forests and tree crops account for 3.62% and 3.52% of the state's area, respectively (Anonymous, 2017). According to the 1975 soil taxonomy, Haryana's soils are classified into four orders: Inceptisols (58%), Entisols (29%), Aridisols (9%), and Alfisols (2%).

Inceptisols are young soils beginning to develop, marked by a cambic horizon and typically formed from igneous, sedimentary, or metamorphic rocks (Muslim, 2020; Marbun, 2016). Entisols are recently formed soils with little profile development, usually only an A horizon, and occur worldwide, often in areas with severe erosion or heavy agriculture (Islam et al., 2021; Fu et al., 2024; Dai et al., 2022). Aridisols are dry, desert soils with low organic matter, sparse vegetation, and are the most widespread globally (Ogura et al., 2016; Khademi and Mermut, 2003). Alfisols are fertile mineral soils found in sub-humid and humid regions, characterized by clay accumulation in the B-horizon and a base saturation of at least 35%, supporting productive agriculture and deciduous forests (Sharma et al., 2008; Bekele and Birhan, 2021; Adams et al., 2019; Aide, 2021).

Soil microorganisms are essential for ecological processes such as organic matter decomposition, nutrient cycling, soil structure formation, and plant health (Chene et al., 2024). Factors like soil type, land use, vegetation, and management shape their composition and activity. Land use changes, especially between

forests and agricultural lands, significantly affect soil microbial diversity and function. A gram of soil can contain over 90 million bacteria that aid plant nutrient uptake by converting nutrients into available forms. Soil enzymes accelerate decomposition and nutrient release, with various microbes and enzymes, such as urease, dehydrogenase, phosphatases, arylsulphatase, glucosidases, laccase, cellulases, and amidases involved in C, N, P, and S cycling (Neemisha and Sharma, 2022). Urease facilitates urea hydrolysis, making N accessible for plants (Koçak, 2020), while dehydrogenase is key to soil biochemical cycles (Kumar et al., 2013), and alkaline phosphatase recycles organic phosphorus.

This study aims to perform a comparative analysis of microbiological properties across forest and agricultural soils within the dominant soil orders of Haryana. The objective is to understand how land use and soil taxonomy interact to shape microbial communities and their ecological functions. The results of this research will contribute to the knowledge base necessary for promoting soil health, sustainable land use, and ecosystem resilience in the region.

2. MATERIAL AND METHODS

2.1 Study Area

The present investigation was conducted to compare the microbiological properties of forest and agricultural/horticultural soils across different soil orders in Haryana, India. Soil sampling was carried out across four major soil orders: Inceptisols, Entisols, Aridisols, and Alfisols.

Representative sites were selected across the districts of Sirsa, Hisar, Jind, Karnal, Ambala, Yamunanagar, Mahendergarh, and Bhiwani. From each soil order, five sites were selected from both forest and agricultural/horticultural lands, making a total of 40 composite samples (4 soil orders × 2 land uses × 5 replicates). Soil samples were collected from a depth of 0–20 cm using a soil auger. At each site, samples were collected from multiple random spots within the plot and combined to form a single composite sample per plot. Three sub-samples were collected from each field and thoroughly mixed to ensure representativeness.

2.2 Collection of Soil Samples

The collected soil samples accurately represented the characteristics of the sampled area. Care was taken to avoid non-representative areas such as recently fertilized fields, bunds, irrigation channels, tree bases, paths, buildings, wells, and compost piles. Each composite sample was divided into two portions:

- One portion was air-dried, sieved (2 mm mesh), and stored for analysis of physicochemical properties.
- The other portion was stored in moist conditions at 4°C and used immediately for microbiological analyses.

2.3 Processing of Soil Samples

2.3.1 Dehydrogenase

Dehydrogenase activity was quantified using the TTC reduction method (Casida et al., 1964), which measures triphenyl formazan (TPF) production from 2,3,5-triphenyl tetrazolium chloride (TTC). Soil samples (5g) were combined with 2.5 ml distilled water and 3% TTC solution, then incubated at 37°C for 24 hours. Post-incubation, methanol (10 ml) was added to stop the reaction and extract TPF, followed by vigorous shaking and filtration through Whatman No. 1 filter paper. The resulting solution's absorbance was measured spectrophotometrically at 485 nm to determine enzyme activity levels.

2.3.2 Urase activity

Tabatabai and Bremner's (1972) method was adopted for the determination of urease activity, which is based on the ammonia released determination after incubating the soil with a

solution of urea for two hours at 37 °C. The result is expressed in µg of N-NH₄⁺ per gram of dry soil per hour.

2.3.3 Alkaline phosphatase activity

Alkaline phosphatase activity was assessed according to the method described by Tabatabai and Bremner (1969). For this, 1 g of soil was placed in a flask and treated with 0.2 ml toluene, 4 ml of modified universal buffer (MUB), and 1 ml of p-nitrophenyl phosphate solution. The mixture was incubated for one hour, after which 1 ml of 0.5 M CaCl₂ and 4 ml of 0.5 M NaOH were added. The contents were stirred briefly, filtered through Whatman No. 1 filter paper, and the absorbance of the filtrate was measured at 420 nm using a spectrophotometer.

2.3.4 Microbial biomass carbon

Microbial biomass carbon (MBC) was estimated using the fumigation-extraction method (Vance et al., 1987). Ten grams of soil were fumigated with chloroform for 24 hours in the dark, while a separate 10 g sample was kept refrigerated. Both samples were extracted with 0.5 M K₂SO₄, treated with acids, heated, diluted, and then titrated with ferrous ammonium sulphate to calculate MBC.

$$\text{MBC (Mg/g soil)} = \frac{\text{OCF} - \text{OCUF}}{K}$$

where,

- OCF = Total amount of EC (Extractable C) in fumigated soil.
- OCUF = Total amount of EC (Extractable C) in non-fumigated soil.
- K = The proportion of microbial C evolved as CO₂ = 0.45 for 10 days of incubation at 25°C (Jenkinson and Ladd, 1981).

2.4 Microbial Biomass Nitrogen

Microbial biomass nitrogen (MBN) was measured using the fumigation-extraction method (Brookes et al., 1985). Ten grams of soil were fumigated with chloroform for 24 hours, while another 10 g remained unfumigated. Both were extracted with 0.5 M K₂SO₄, and 25 ml of extract was treated with MgO for NH₄-N and then Devarda alloy for NO₃-N analysis via Kjeldahl distillation. The released ammonia was titrated with 0.01 N H₂SO₄, and MBN was calculated from these results.

Mineralized NH₄-N (ppm)=(R-B) x 56

Microbial biomass nitrogen= fum NH₄-N – unfum NH₄-N

2.5 Total Microbial Count

Microbial populations were assessed using the serial dilution technique by Salle (1973). One gram of soil was mixed with 10 mL sterile water to form an initial dilution, followed by a series of tenfold dilutions up to 10⁻⁵. Selected dilutions were plated on specific agar media under sterile conditions. After pouring and setting the media, the plates were incubated at 28±2°C for 2–5 days. The resulting colonies were counted and expressed as colony-forming units per gram of soil (CFU g⁻¹), enabling quantitative comparison of culturable microbes across samples.

Table 1. Growth media used for microbial analysis

Sr. No.	Microbes	Media
1.	Bacteria	Nutrient Agar
2.	Fungi	Potato Dextrose Agar
3.	Actinomycetes	Ken-Knight 's Medium

2.6 Statistical Analysis

The significance of treatment effects was analyzed using two-factor analysis in Origin software.

3. RESULTS

Microbial properties of Aridisols under forest and agricultural land use are summarized in Table 2. Urease activity ranged from 26.60 to 79.15 µg NH₄-N g h⁻¹ overall, with forest soils showing 65.00–79.15 (mean 72.29) and agricultural soils 26.60–45.26 (mean 38.36). The highest and lowest urease activities in forests were at Balsmand (Hisar) and Mahendergarh, respectively; in agriculture, the highest at Balsmand (Hisar) and the lowest at Bandakheri (Hisar). Alkaline phosphatase activity (APA) ranged from 209.50 to 858.00 µg PNP/g/h overall. Forest soils had 401.50–858.00 (mean 558.60), highest at Balsmand (Hisar) and lowest at Mahendergarh. Agricultural soils had 209.50–544.50 (mean 406.80), highest at Mahendergarh and lowest at Payal (Hisar). Dehydrogenase activity (DHA) ranged from 24.00 to 60.25 TPF/g/h overall. Forest soils ranged 45.80–60.25 (mean 54.90), highest at Balsmand (Hisar) and lowest at Mahendergarh. Agricultural soils ranged 24.00–29.45 (mean 27.13), highest at

Balsmand (Hisar) and lowest at Mahendergarh. Microbial biomass carbon (MBC) ranged from 99.20 to 355.30 mg/kg overall. Forest soils had 300.18–355.30 (mean 325.84), highest at Mahendergarh and lowest at Siwan Mandi (Bhiwani). Agricultural soils had 99.20–126.00 (mean 107.33), highest at Mahendergarh and lowest at Siwan Mandi (Bhiwani). Microbial biomass nitrogen (MBN) ranged from 24.40 to 68.90 mg/kg overall. Forest soils had 52.60–68.90 (mean 60.32), highest at Bandakheri (Hisar) and lowest at Mahendergarh. Agricultural soils had 24.40–32.10 (mean 28.32), highest at Siwan Mandi (Bhiwani) and lowest at Bandakheri (Hisar). Forest soils consistently showed higher urease, APA, DHA, MBC, and MBN at all locations than agricultural soils.

Microbial properties in Entisols of Haryana under forest and agricultural land use are shown in Table 3. Urease activity ranged from 33.00 to 127.40 µg NH₄-N g h⁻¹ overall, with forest soils at 42.00–127.40 (mean 77.84) and agricultural soils at 33.00–56.00 (mean 40.02). The highest and lowest urease activities in forests were at Segta (Ambala) and Bisamgarh (Ambala), respectively; in agriculture, the highest was at Kelaniya (Sirsa) and the lowest at Sahuwala (Sirsa). Alkaline phosphatase activity (APA) ranged from 556.50 to 949.20 µg PNP/g/h overall. Forest soils had 631.50–949.20 (mean 792.24), highest at Ambala (Sahapur) and lowest at Sakaraho (Ambala). Agricultural soils had 556.50–723.50 (mean 629.30), highest at Meerpur (Sirsa) and lowest at Sahuwala (Sirsa). Dehydrogenase activity (DHA) ranged from 32.26 to 62.12 TPF/g/h overall. Forest soils ranged 55.65–62.12 (mean 59.38), highest at Balsmand (Hisar) and lowest at Mahendergarh. Agricultural soils ranged 32.26–36.42 (mean 33.95), highest at Nanakpura (Sirsa) and lowest at Meerpur (Sirsa). Microbial biomass carbon (MBC) ranged from 112.20 to 371.40 mg/kg overall. Forest soils had 302.00–371.40 (mean 332.87), highest at Segta (Ambala) and lowest at Sakaraho (Ambala). Agricultural soils had 112.20–124.20 (mean 120.20), highest at Meerpur (Sirsa) and lowest at Jhopra (Sirsa). Microbial biomass nitrogen (MBN) ranged from 30.60 to 78.60 mg/kg overall. Forest soils had 63.80–78.60 (mean 70.36), highest at Dukhari (Ambala) and lowest at Sakaraho (Ambala). Agricultural soils had 30.60–34.60 (mean 33.14), highest at Nanakpura (Sirsa) and lowest at Jhopra (Sirsa). Across all sites, forest soils consistently showed higher urease activity, APA, DHA, MBC, and MBN than agricultural soils.

Table 2. Effect of land use systems and orders on microbial properties in Aridisols

Locations	Urease ($\mu\text{gNH}_4\text{-N g h}^{-1}$)	APA ($\mu\text{gPNP/g/h}$)	DHA ($\mu\text{g TPF/g/ h}$)	MBC (mg kg^{-1})	MBN (mg kg^{-1})
Forest land use					
L ₁	76.56	525.00	58.45	320.30	68.90
L ₂	79.15	858.00	60.25	313.20	59.90
L ₃	68.45	428.00	55.12	300.18	60.00
L ₄	72.30	580.50	45.80	355.30	60.20
L ₅	65.00	401.50	54.90	340.20	52.60
Mean	72.29	558.60	54.90	325.84	60.32
SD	5.77	182.34	5.57	21.93	5.78
SEM	± 2.58	± 81.54	± 2.49	± 9.81	± 2.58
Agricultural land use					
L ₆	40.12	413.00	28.52	99.20	32.10
L ₇	45.26	354.00	29.45	102.23	30.20
L ₈	42.00	209.50	24.56	100.00	28.60
L ₉	26.60	513.00	29.12	109.20	24.40
L ₁₀	37.80	544.50	24.00	126.00	26.30
Mean	38.36	406.80	27.13	107.33	28.32
SD	7.05	134.60	2.63	11.16	3.06
SEM	± 3.15	± 60.00	± 1.18	± 4.99	± 1.37

Table 3. Influence of land use systems and orders on microbial properties in Entisols

Locations	Urease ($\mu\text{gNH}_4\text{-N g h}^{-1}$)	APA ($\mu\text{gPNP/g/h}$)	DHA ($\mu\text{g TPF/g/ h}$)	MBC (mg kg^{-1})	MBN (mg kg^{-1})
Forest land use					
L ₁₁	42.00	869.00	55.65	307.04	69.20
L ₁₂	127.40	798.00	62.12	371.40	67.60
L ₁₃	81.20	631.50	59.25	302.00	63.80
L ₁₄	98.00	949.20	60.45	361.10	72.60
L ₁₅	40.60	713.50	59.43	322.80	78.60
Mean	77.84	792.24	59.38	332.87	70.36
SD	37.23	125.10	2.38	31.63	5.59
SEM	± 16.65	± 55.95	± 1.06	± 14.15	± 2.50
Agricultural land use					
L ₁₆	35.00	654.50	33.45	112.20	30.60
L ₁₇	34.10	723.50	32.26	124.20	35.30
L ₁₈	56.00	615.50	34.68	120.20	32.60
L ₁₉	42.00	596.50	36.42	123.00	34.60
L ₂₀	33.00	556.50	32.95	121.40	32.60
Mean	40.02	629.30	33.95	120.20	33.14
SD	9.60	63.39	1.64	4.72	1.86
SEM	± 4.29	± 28.35	± 0.73	± 2.11	± 0.83

Microbial properties in Inceptisols of Haryana under forest and agricultural land use are summarized in Table 4. Urease activity ranged from 26.60 to 90.00 $\mu\text{g NH}_4\text{-N g h}^{-1}$ overall, with forest soils at 46.90–90.00 (mean 73.18) and agricultural soils at 26.60–67.90 (mean 51.48). The highest and lowest urease activities in forests were at Bhitha Bilaspur (Yamuna Nagar) and Aadi Badri (Yamuna Nagar), respectively; in agriculture, the highest at Kathgarh (Yamuna Nagar) and the lowest at Kisanpura (Yamuna

Nagar). Alkaline phosphatase activity (APA) ranged from 692.00 to 984.00 $\mu\text{g PNP/g/h}$ overall. Forest soils had 798.50–984.00 (mean 911.80), highest at near the canal (Jind) and lowest at Aadi Badri (Yamuna Nagar). Agricultural soils had 692.00–845.50 (mean 779.25), highest at Bahadurpur (Yamuna Nagar) and lowest at Kisanpura (Yamuna Nagar). Dehydrogenase activity (DHA) ranged from 29.78 to 60.25 TPF/g/h overall. Forest soils ranged 55.85–60.25 (mean 58.04), highest at

near the canal (Jind) and lowest at Bhitha Bilaspur (Yamuna Nagar). Agricultural soils ranged 29.78–34.25 (mean 31.45), highest at Kathgarh (Yamuna Nagar) and lowest at Bahadurpur (Yamuna Nagar). Microbial biomass carbon (MBC) ranged from 122.23 to 386.00 mg/kg overall. Forest soils had 368.45–386.00 (mean 375.49), highest at Kisanpura (Yamuna Nagar) and lowest at Bhitha Bilaspur (Yamuna Nagar). Agricultural soils had 122.23–177.58 (mean 152.46), highest at Bahadurpur (Yamuna Nagar) and lowest at Samthali (Yamuna Nagar). Microbial biomass nitrogen (MBN) ranged from 30.30 to 87.80 mg/kg overall. Forest soils had 75.00–87.80 (mean 81.02), highest at Kisanpura (Yamuna Nagar) and lowest at Bhitha Bilaspur (Yamuna Nagar). Agricultural soils had 30.30–39.80 (mean 34.66), highest at Gumthala (Yamuna Nagar) and lowest at Kisanpura (Yamuna Nagar).

At all sites, forest soils showed higher urease activity, APA, DHA, MBC, and MBN than agricultural soils.

Microbial properties in Alfisols of Haryana under forest and agricultural land use are summarized in Table 5. Urease activity ranged from 42.00 to 95.00 $\mu\text{g NH}_4\text{-N g h}^{-1}$ overall, with forest soils at 72.70–95.00 (mean 83.78) and agricultural soils at 42.00–52.00 (mean 47.76). The highest and lowest urease activities in forests were at Siwan Mandi (Bhiwani) and Bandakheri (Hisar),

respectively; in agriculture, the highest was at Balsmand (Hisar) and the lowest at Siwan Mandi (Bhiwani). Alkaline phosphatase activity (APA) in forest soils ranged from 736.00 to 1031.40 (mean 937.60), highest at Bundanpur (Karnal) and lowest at Katlaheri (Karnal). In agriculture, APA ranged from 748.00 to 848.00 (mean 804.98), highest at Rambha (Karnal) and lowest at Janesaro (Karnal). Dehydrogenase activity (DHA) overall ranged from 30.90 to 70.15 TPF/g/h. In forests, DHA ranged from 56.12–70.15 (mean 65.25), highest at Katlaheri (Karnal) and lowest at Alawala (Karnal). In agriculture, DHA ranged from 30.90–34.56 (mean 32.76), highest at Bijna (Karnal) and lowest at Janesaro (Karnal). Microbial biomass carbon (MBC) ranged from 176.26 to 490.20 mg/kg overall. Forest soils had 380.42–490.20 (mean 383.89), highest at Ghoghripur (Karnal) and lowest at Katlaheri (Karnal). Agricultural soils had 176.26–204.24 (mean 193.33), highest at Tarawari (Karnal) and lowest at Rambha (Karnal). Microbial biomass nitrogen (MBN) ranged from 32.60 to 90.60 mg/kg overall. Forest soils had 84.50–90.60 (mean 88.82), highest at Alawala (Karnal) and lowest at Bundanpur (Karnal). Agricultural soils had 32.60–42.20 (mean 37.02), highest at Gumto (Karnal) and lowest at Bijna (Karnal).

At all sites, forest soils consistently showed higher urease activity, APA, DHA, MBC, and MBN than agricultural soils.

Table 4. Effect of different soil orders and land use systems on microbial properties in Inceptisols

Locations	Urease ($\mu\text{gNH}_4\text{-N g h}^{-1}$)	APA ($\mu\text{gPNP/g/h}$)	DHA ($\mu\text{g TPF/g/h}$)	MBC (mg kg^{-1})	MBN (mg kg^{-1})
Forest land use					
L ₂₁	70.00	984.00	60.25	369.20	82.70
L ₂₂	46.90	798.50	59.54	377.23	79.40
L ₂₃	90.00	973.80	55.85	368.45	75.00
L ₂₄	77.00	935.90	56.45	376.56	80.20
L ₂₅	82.00	866.80	58.12	386.00	87.80
Mean	73.18	911.80	58.04	375.49	81.02
SD	16.40	78.26	1.90	7.14	4.70
SEM	± 7.34	± 35.00	± 0.85	± 3.19	± 2.10
Agricultural land use					
L ₂₆	46.90	765.00	30.63	122.23	36.20
L ₂₇	67.90	809.00	34.25	177.36	32.00
L ₂₈	26.60	692.00	30.12	155.59	30.30
L ₂₉	60.00	845.50	29.78	177.58	35.00
L ₃₀	56.00	784.74	32.45	129.54	39.80
Mean	51.48	779.25	31.45	152.46	34.66
SD	15.83	57.27	1.88	25.98	3.71
SEM	± 7.08	± 25.61	± 0.84	± 11.62	± 1.66

Table 5. Effect of land use system and soil orders on microbial properties in Alfisols

Locations	Urease ($\mu\text{gNH}_4\text{-N g h}^{-1}$)	APA ($\mu\text{gPNP/g/h}$)	DHA ($\mu\text{g TPF/g/ h}$)	MBC (mg kg^{-1})	MBN (mg kg^{-1})
Forest land use					
L ₃₁	72.70	1017.60	65.25	490.20	88.60
L ₃₂	79.40	1031.40	68.20	473.24	84.50
L ₃₃	95.00	736.00	70.15	470.75	90.10
L ₃₄	84.00	923.00	66.55	380.42	90.30
L ₃₅	87.80	980.00	56.12	446.82	90.60
Mean	83.78	937.60	65.25	383.89	88.82
SD	8.43	120.6	5.43	193.74	2.54
SEM	± 3.77	53.78	2.43	86.64	1.13
Agricultural land use					
L ₃₆	42.00	776.00	32.16	204.24	34.90
L ₃₇	52.00	821.50	33.45	193.75	42.20
L ₃₈	50.00	748.00	30.90	194.42	35.20
L ₃₉	45.00	848.00	32.75	176.26	40.20
L ₄₀	49.80	831.40	34.56	198.00	32.60
Mean	47.76	804.98	32.76	193.33	37.02
SD	4.12	41.56	1.37	10.41	4.01
SEM	± 1.84	± 18.59	± 0.61	± 4.66	± 1.79

Fig. 1 shows that across all soil orders, mean bacterial counts were higher in forest land use than in agricultural systems. In forests, bacterial counts ranged from 4.94 to 6.68 $\text{cfu} \times 10^5 \text{ g}^{-1}$ soil, while in agriculture they ranged from 3.64 to 4.60 $\text{cfu} \times 10^5 \text{ g}^{-1}$ soil. Mean bacterial counts in forest soils were 4.94 (Aridisols), 5.20 (Entisols), 6.01 (Inceptisols), and 6.68 (Alfisols); in agricultural soils, the means were 3.64, 4.02, 4.14, and 4.60 $\text{cfu} \times 10^5 \text{ g}^{-1}$ soil for the same respective orders. The highest bacterial count (6.68 $\text{cfu} \times 10^5 \text{ g}^{-1}$) was in forest Alfisols, and the lowest (3.64 $\text{cfu} \times 10^5 \text{ g}^{-1}$) in agricultural Ardisols. Overall,

bacterial counts followed the order: Alfisols > Inceptisols > Entisols > Ardisols in both land use systems.

Fig. 2 shows that fungi counts were consistently higher in forest soils than in agricultural soils across all soil orders. In forests, fungi count ranged from 2.64 to 4.06 $\text{cfu} \times 10^3 \text{ g}^{-1}$ soil, while in agriculture they ranged from 1.84 to 3.18 $\text{cfu} \times 10^3 \text{ g}^{-1}$ soil. Mean fungi count in forest soils were 2.64 (Aridisols), 3.24 (Entisols), 4.06 (Inceptisols), and 3.98 (Alfisols); in agricultural soils, the means were 1.84, 2.24, 3.18,

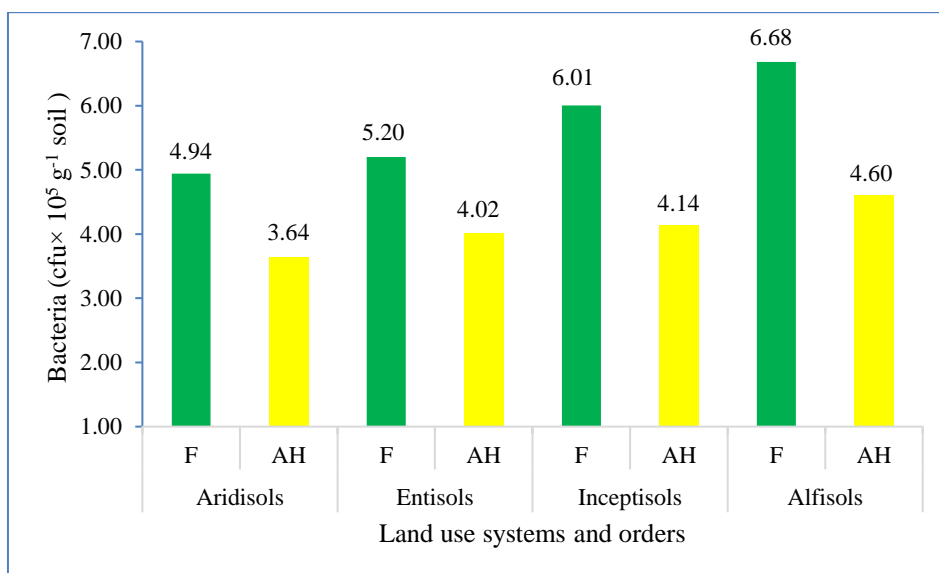


Fig. 1. Bacteria count in different soil orders of Haryana

and $2.80 \text{ cfu} \times 10^3 \text{ g}^{-1}$ soil, respectively. The highest fungi count ($4.06 \text{ cfu} \times 10^3 \text{ g}^{-1}$) was in forest Inceptisols, and the lowest ($1.84 \text{ cfu} \times 10^3 \text{ g}^{-1}$) in agricultural Aridisols. Fungi count followed the sequence: Inceptisols > Alfisols > Entisols > Aridisols in both land use systems.

Fig. 3 shows that actinomycete counts were consistently higher in forest soils than in agricultural soils across all soil orders. In forests, counts ranged from 1.44 to $2.36 \text{ cfu} \times 10^4 \text{ g}^{-1}$ soil, while in agriculture they ranged from 1.10 to

$1.78 \text{ cfu} \times 10^4 \text{ g}^{-1}$ soil. Mean actinomycete counts in forest soils were 1.44 (Aridisols), 1.94 (Entisols), 2.00 (Inceptisols), and 2.36 (Alfisols); in agriculture, the means were 1.11 , 1.26 , 1.10 , and $1.78 \text{ cfu} \times 10^4 \text{ g}^{-1}$ soil, respectively. The highest count ($2.36 \text{ cfu} \times 10^4 \text{ g}^{-1}$) was in forest Alfisols, and the lowest ($1.10 \text{ cfu} \times 10^4 \text{ g}^{-1}$) in agricultural Inceptisols. In forests, actinomycetes followed the order: Alfisols > Inceptisols > Entisols > Aridisols; in agriculture: Alfisols > Entisols > Aridisols > Inceptisols.

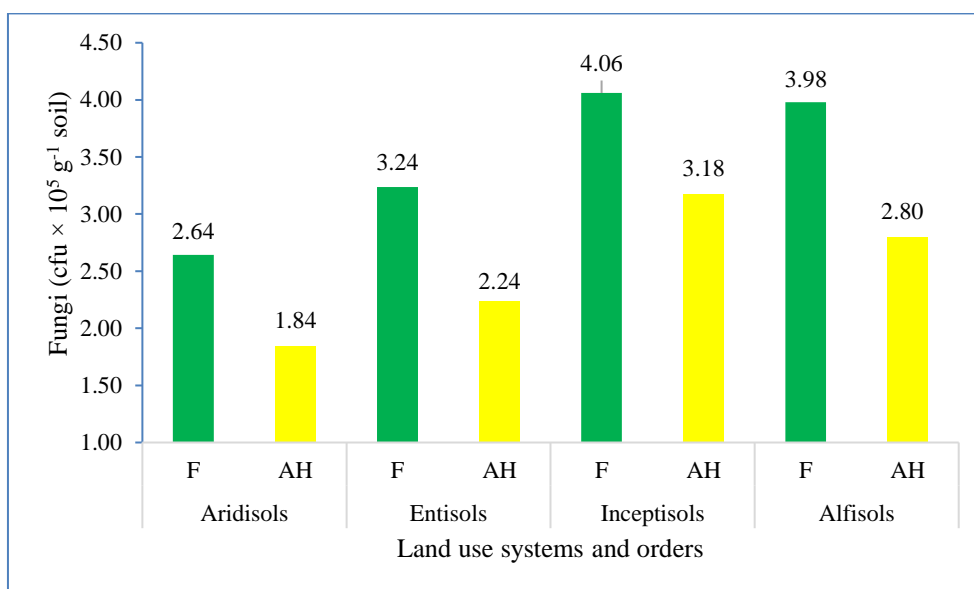


Fig. 2. Fungi count in different soil orders of Haryana

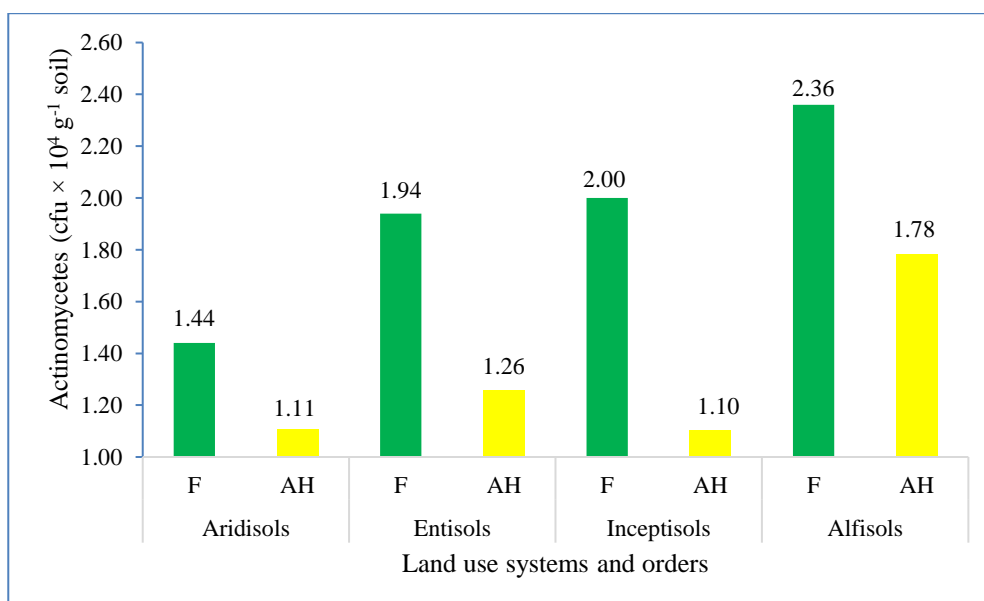


Fig. 3. Actinomycetes count in different soil orders of Haryana

Table 6. Effect of land use and orders on microbial properties

Parameters	Urease activity ($\mu\text{gNH}_4\text{-N g h}^{-1}$)	APA ($\mu\text{gPNP/g/h}$)	DHA ($\mu\text{g TPF/g/ h}$)	MBC (mg kg^{-1})	MBN (mg kg^{-1})
Land use					
Forest	76.77 ^a (\pm 4.42)	800.06 ^a (\pm 43.73)	59.39 ^a (\pm 1.21)	371.61 ^a (\pm 12.99)	75.13 ^a (\pm 2.66)
Agri/Horti	45.25 ^b (\pm 2.65)	655.08 ^b (\pm 40.03)	31.32 ^b (\pm 0.71)	143.33 ^b (\pm 8.23)	33.29 ^b (\pm 0.99)
p < 0.05	0.0001	2.1420	0.0001	0.0001	0.0001
Orders					
Aridisols	55.32 ^a (\pm 5.98)	482.70 ^c (\pm 54.01)	41.01 ^c (\pm 4.81)	216.58 ^c (\pm 36.78)	44.32 ^d (\pm 5.50)
Entisols	60.62 ^a (\pm 10.24)	710.77 ^b (\pm 40.14)	46.67 ^{ab} (\pm 4.28)	226.53 ^c (\pm 36.08)	51.75 ^c (\pm 6.32)
Inceptisols	62.33 ^a (\pm 6.01)	845.52 ^a (\pm 30.10)	44.74 ^{bc} (\pm 4.46)	263.97 ^b (\pm 37.60)	57.84 ^b (\pm 7.82)
Alfisols	65.77 ^a (\pm 6.32)	871.29 ^a (\pm 34.75)	49.01 ^a (\pm 5.54)	322.81 ^a (\pm 44.15)	62.92 ^a (\pm 8.69)
p < 0.05	0.5844	0.0001	0.0001	0.0001	0.0001
Land use x orders	0.7691	0.9864	0.0999	0.1309	0.0001

3.1 Overall Mean Comparison

The content in Table 6 indicates that the urease activity significantly differed between the two land use systems, where the forest land use system showed a significantly higher ($76.77 \mu\text{gNH}_4\text{-N g h}^{-1}$) compared to the agri/horti land use systems ($45.25 \mu\text{gNH}_4\text{-N g h}^{-1}$). There was no significant difference among the different soil orders; however, the highest mean value ($65.77 \mu\text{gNH}_4\text{-N g h}^{-1}$) was observed in Alfisols, while the lowest ($55.32 \mu\text{gNH}_4\text{-N g h}^{-1}$) was recorded in Aridisols. A significant difference in APA was observed between the two land use systems, with the forest land use system exhibiting notably higher values ($800.06 \mu\text{gPNP/g/h}$) than the agri/horti land use system ($655.08 \mu\text{gPNP/g/h}$). Among the soil orders, Alfisols exhibited significantly higher ($871.29 \mu\text{gPNP/g/h}$) APA than Aridisols and Entisols (480.70 , $710.77 \mu\text{gPNP/g/h}$), which was statistically at par with Inceptisols. A significant difference in DHA was observed between the forest and agri/horti land use systems, with forest land exhibiting significantly higher mean values ($59.39 \mu\text{g TPF/g/h}$) than agri/horti land ($31.32 \mu\text{g TPF/g/h}$). Among soil orders, Alfisols recorded significantly higher ($49.01 \mu\text{g TPF/g/h}$) DHA than Aridisols and Inceptisols (41.01 , $44.74 \mu\text{g TPF/g/h}$), however, it was statistically at par with Entisols. Forest land use systems had significantly higher MBC (371.61 mg/kg) and MBN (75.13 mg/kg) than agri/horti systems (143.33 and 33.29 mg/kg , respectively). Among soil orders, Alfisols showed the highest MBC (322.81 mg/kg) and MBN (62.92 mg/kg), while Aridisols, Entisols, and Inceptisols had lower values.

4. DISCUSSION

Our study found that urease activity was consistently higher in forest soils than in agricultural soils across all soil orders. This aligns with Bhat (2022), who reported significantly greater urease activity in forest soils than agricultural paddy soils, attributing this to higher organic carbon and microbial biomass. Similarly, Meena and Rao (2021) observed higher urease activity in mixed forest cover than in agricultural fields, linking the increase to greater organic matter and microbial activity. Błońska et al. (2017) also noted elevated urease activity in forest soils, emphasizing the impact of organic matter and land use on enzyme dynamics. These findings are further supported by Freitas et al. (2013), Sehwat (1984), and Fenn et al. (1992).

For dehydrogenase activity (DHA), our results showed higher values in forest land use systems across all soil orders, with the highest DHA ($65.25 \mu\text{g TPF/g/h}$) in forest Alfisols and the lowest ($27.13 \mu\text{g TPF/g/h}$) in agricultural Aridisols. Velmourougane et al. (2013) found that DHA was significantly higher in sub-humid, moist regions and lower in arid areas, highlighting the influence of climate and land use on DHA levels. Our findings are consistent with Pandey et al. (2005) and Kang et al. (2009) for forest soils, and Gaiind and Nain (2011) for agricultural soils. Forest soils benefit from regular litter input and decomposition, which boost organic matter and microbial activity, whereas prolonged chemical fertilizer use in agriculture can suppress dehydrogenase activity by inhibiting microbial growth, as also reported by Singh et al. (2014).

The mean alkaline phosphatase activity (APA) was generally higher in forest land use systems than in agricultural systems across all soil orders, with values ranging from 406.80 to $937.60 \mu\text{g PNP/g/h}$. The highest mean APA was found in forest Alfisols, while the lowest was in agricultural Aridisols. These findings are consistent with Mir et al. (2023), who reported significantly greater APA in forest soils compared to cultivated soils, attributing this to higher organic matter and microbial diversity in forests. Similarly, Singh et al. (2014) observed that undisturbed forest soils had elevated APA due to richer organic content and microbial activity, whereas intensive agriculture reduced enzyme activity. Our results are also supported by Uthappa et al. (2024), Ma et al. (2024), and Jiang et al. (2024).

Across all soil orders, our study found that mean microbial biomass carbon (MBC) was consistently higher in forest soils than in agricultural soils, with the highest MBC ($383.89 \text{ mg kg}^{-1}$) in forest Alfisols and the lowest ($107.33 \text{ mg kg}^{-1}$) in agricultural Aridisols. These results are in line with Apoorva et al. (2022), who reported maximum MBC in forest soils and lower values under intensive cropping. Padbhushan et al. (2022) also observed a 26% decline in MBC following conversion from forest to cultivated land, highlighting the negative impact of land-use change on soil microbial properties. Similarly, Meena and Rao (2021) found significantly higher MBC in forested areas, while Singh et al. (2022) noted that agroforestry systems supported greater MBC than monoculture plantations or croplands, attributing this to higher organic matter inputs and better soil structure. Pan et al. (2024) further demonstrated that forest land use

can increase MBC by up to 84.48%, whereas conversion to agriculture reduces microbial indicators. These findings, supported by Jindo et al. (2024) and Xiang et al. (2017), reinforce that forest and tree-based systems enhance soil microbial biomass and overall soil health, consistent with our observations.

Our results showed that mean microbial biomass nitrogen (MBN) was higher in forest soils than in agricultural soils across all soil orders, with values ranging from 28.32 to 88.82 mg kg⁻¹. The highest mean MBN was observed in forest Alfisols, while the lowest was in agricultural Aridisols. These findings are consistent with Fang et al. (2014), who reported significantly greater MBC and MBN in natural forests compared to croplands and plantations. Our results also align with those of Karimzadeh et al. (2025), Pan et al. (2024), Deng et al. (2016), Kara and Bolat (2008), and Wang et al. (2020), all of whom found higher microbial biomass in forested systems than in agricultural lands.

The populations of bacteria, fungi, and actinomycetes were consistently higher in forest land use systems than in agricultural systems across all soil orders. Bacterial counts ranged from 4.94 to 6.68 cfu × 10⁵ g⁻¹ soil in forests and 3.64 to 4.60 cfu × 10⁵ g⁻¹ in agriculture. Fungi counts were 2.64 to 4.06 cfu × 10³ g⁻¹ in forests and 1.84 to 3.18 cfu × 10³ g⁻¹ in agriculture. Actinomycetes ranged from 1.44 to 2.36 cfu × 10⁴ g⁻¹ in forests and 1.10 to 1.78 cfu × 10⁴ g⁻¹ in agriculture. These findings are supported by Mir et al. (2023), who reported the highest bacterial counts in forest soils, attributed to greater substrate availability, vegetation cover, and favorable soil conditions, while cultivated soils had reduced bacterial activity due to limited organic inputs and decreased counts with soil depth. Wani et al. (2018) also found higher populations of bacteria, fungi, and actinomycetes in forests, likely due to greater organic matter. Our results are further supported by Gong et al. (2022) and Zhang et al. (2016).

5. CONCLUSION

This study clearly shows that forest land use supports significantly higher soil microbial activity and biomass than agricultural systems across all major soil orders in Haryana. Alfisols under forest cover exhibited the greatest microbial enzyme activities and biomass, while Aridisols under agriculture had the lowest. Enhanced organic matter and favorable conditions in forests

promote diverse and active microbial communities, whereas intensive farming reduces microbial health. These findings highlight the critical impact of land use on soil biological health and underscore the need for sustainable management practices that maintain organic inputs and protect soil microbial vitality to ensure long-term soil fertility and ecosystem sustainability.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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