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# Influence of Diversified Cropping Systems on Yield Sustainability and Soil Properties in the *Tarai* Region of Uttarakhand

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*This work was carried out in collaboration between both authors. Author Shikha contributed to conceptualization, methodology, investigation, data curation, writing—original draft, and writing—review and editing. Author APS contributed to conceptualization, methodology, resources, visualization, writing—review and editing, and supervision. Both authors read and approved the final manuscript.*

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## Abstract

Modern agriculture in the *Tarai* region faces increasing pressure from declining productivity and deteriorating soil health. A two-year field study was conducted during 2023-24 and 2024-25 at Pantnagar, Uttarakhand, to evaluate the influence of eight diversified cropping systems on Yield Sustainability Index (YSI) and selected soil properties at 0-15 cm and 15-30 cm depths. The soil parameters assessed included pH, electrical conductivity (EC), bulk density (BD), and water holding capacity (WHC). The YSI varied significantly among cropping systems in both years. Sweet corn-broccoli-okra recorded the highest YSI values of 4.32 and 4.59 in 2023-24 and 2024-25, respectively, whereas black gram-gram-*Sesbania* recorded the lowest value of 1.00 in both years. Soil pH remained statistically unaffected by cropping systems at both depths. At the 0-15 cm depth, EC and BD differed significantly among systems, while differences at 15-30 cm were non-significant. Basmati rice-potato-maize recorded higher EC, whereas rice-wheat-fallow recorded

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higher BD. Legume- and green manure-based systems, particularly black gram-gram-*Sesbania* and rice-lentil-cowpea, improved WHC at both depths. The findings indicate that sweet corn-broccoli-okra enhanced yield sustainability, while legume-inclusive systems contributed to improved soil physical properties. Diversified cropping systems may therefore support productivity and soil quality in the *Tarai* region of the Indo-Gangetic Plains.

*Keywords: Crop diversification; yield sustainability index; soil bulk density; water holding capacity; Indo-Gangetic Plains.*

## 1. Introduction

Closing yield gaps is essential for achieving various United Nations Sustainable Development Goals by enhancing agricultural productivity and sustainability (Gerber et al., 2024). Continuous cultivation of the rice-wheat cropping system in India has resulted in several challenges, including yield stagnation, declining soil health, poor nutrient-use efficiency, and increased incidence of pests and diseases (Sarkar & Rakshit, 2020; Kaur et al., 2023). Diversified cropping systems can improve agricultural sustainability by providing several benefits, such as pest regulation, increased resilience to climate-related stresses, and reduced fertilizer requirements through legume inclusion, thereby contributing to improved crop productivity and profitability (Waha et al., 2020). In this context, agricultural intensification through crop diversification offers a promising approach to increasing crop productivity per unit area by improving yields and enhancing cropping intensity.

Cropping systems influence soil physical, chemical, and biological properties (Varathiyan et al., 2025). Verma and Sharma (2024) reported that the rice-wheat and maize-wheat systems exhibited higher soil pH, electrical conductivity, available phosphorus, and available potassium, whereas the poplar- and eucalyptus-based systems had greater soil organic carbon and DTPA-extractable micronutrient concentrations. Similarly, Sharma et al. (2009) reported that, compared with the rice-wheat system, the rice-potato-mungbean system increased productivity (59-89%) and improved soil biological properties, while the rice-rapeseed-mungbean system enhanced productivity (12-15%) and improved soil fertility and microbial activity. Furthermore, Ankit et al. (2024) identified soil pH, electrical conductivity, and soil organic carbon as key indicators for assessing soil health under different cropping systems. Cropping systems also influence soil physical properties. For example, Dharumarajan et al. (2013) observed significantly greater soil water-retention characteristics and available water capacity under the paddy-potato-vegetable cropping system than under the paddy-paddy system. The rice-maize cropping system had significantly higher bulk density than the rice-jute system (Rakesh et al., 2020).

The performance of different cropping systems can be evaluated using the Yield Sustainability Index (YSI). This index provides a quantitative measure for comparing the yield sustainability of different cropping systems. However, information on the effects of diversified cropping systems on YSI and soil properties in the Indo-Gangetic Plains, particularly in the *Tarai* region of Uttarakhand, remains limited. Therefore, the present study was conducted to evaluate the effects of different cropping systems on YSI and selected soil properties.

## 2. Materials and Methods

### 2.1 Experimental Site

A two-year field investigation was conducted from June 2023 to June 2025 on diversified cropping systems at the Integrated Farming System Unit Block, N. E. Borlaug Crop Research Centre, Pantnagar. The site is situated in the humid subtropical *Tarai* belt of the Indo-Gangetic Plains, Udham Singh Nagar district, Uttarakhand, India (29° N latitude, 79°30′ E longitude), at an elevation of 244 m above mean sea level. The soil of the experimental field is alluvial in origin and sandy clay loam in texture.

The total annual rainfall recorded during 2023-24 and 2024-25 was 1482.2 and 1692.1 mm, respectively. During 2023-24, the maximum and minimum temperatures were 38.53 and 6.7 °C, respectively, while during 2024-25, they were 39.21 and 8.1 °C, respectively.

### 2.2 Treatments

The experiment comprised eight cropping systems: (T1) rice-wheat-fallow, (T2) rice-lentil-cowpea (a vegetable crop), (T3) basmati rice-potato-maize, (T4) sweet corn-broccoli-okra, (T5) soybean-wheat-cowpea (as grain and fodder), (T6) maize-barley-cowpea (as grain and fodder), (T7) sorghum-berseem-pearl millet, and (T8) black gram-gram-*Sesbania* (as green manure). The treatments were arranged in a randomized complete block design with three replications.

## 2.3 Soil Sampling and Analysis

Soil samples were collected from two depths (0-15 and 15-30 cm). Triplicate soil samples collected from each plot at each depth were composited, air-dried, gently ground, and sieved through a 2-mm mesh before laboratory analysis. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-water suspension following the method of Jackson (1973). Bulk density (BD) was estimated using the core sampler method described by Baver (1949). Water holding capacity (WHC) was determined according to the method described by Piper (1950).

## 2.4 Yield Sustainability Index

The Yield Sustainability Index was calculated using the following formula (Meena et al., 2026):

$$\text{Yield Sustainability Index} = \frac{\text{Actual System Productvity (tha}^{-1}\text{)}}{\text{Minimum System Productvity (tha}^{-1}\text{)}}$$

## 2.5 Statistical Analysis

The data were subjected to analysis of variance (ANOVA), and treatment means were compared using Tukey's honestly significant difference (HSD) at the 5% level of significance ($p \leq 0.05$). All statistical analyses were performed using Statistix 10 software.

# 3. Results and Discussion

## 3.1 pH

Soil pH did not differ significantly among cropping systems at either depth during both years of experimentation (Table 1). At the 0-15 cm depth, mean pH ranged from 7.55 under rice-lentil-cowpea to 7.79 under sorghum-berseem-pearl millet. At the 15-30 cm depth, pH ranged from 7.54 under rice-lentil-cowpea to 7.79 under soybean-wheat-cowpea. The results indicate that soil reaction remained neutral to slightly alkaline across all cropping systems and was largely unaffected by the type of crop diversification practiced over the two-year study period. The non-significant variation in soil pH across the cropping systems may be due to the inherent buffering capacity of the alluvial soil, which resists short-term changes in soil reaction. Soil pH is a relatively stable property, and significant differences are generally observed only after long-term management practices (Daba et al., 2021).

**Table 1. Effect of diversified cropping systems on soil pH at 0-15 cm and 15-30 cm depths**

| Treatment | Cropping Systems | pH | | | |
|---|---|---|---|---|---|
| | | 0-15 cm | | 15-30 cm | |
| | | 2023-24 | 2024-25 | 2023-24 | 2024-25 |
| $T_1$ | Rice-Wheat-Fallow | 7.65±0.12 | 7.65±0.07 | 7.67±0.08 | 7.62±0.13 |
| $T_2$ | Rice-Lentil-Cowpea | 7.58±0.18 | 7.55±0.05 | 7.66±0.09 | 7.54±0.11 |
| $T_3$ | Basmati Rice-Potato-Maize | 7.64±0.12 | 7.63±0.15 | 7.73±0.09 | 7.61±0.13 |
| $T_4$ | Sweet Corn-Broccoli-Okra | 7.74±0.11 | 7.79±0.13 | 7.75±0.14 | 7.64±0.11 |
| $T_5$ | Soybean-Wheat-Cowpea | 7.68±0.07 | 7.64±0.16 | 7.79±0.13 | 7.75±0.15 |
| $T_6$ | Maize-Barley-Cowpea | 7.66±0.11 | 7.62±0.14 | 7.77±0.12 | 7.72±0.17 |
| $T_7$ | Sorghum-Berseem-Pearl millet | 7.75±0.07 | 7.79±0.11 | 7.76±0.14 | 7.63±0.13 |
| $T_8$ | Black gram-Gram-*Sesbania* | 7.73±0.11 | 7.72±0.15 | 7.71±0.11 | 7.70±0.12 |
| *p*-value | | NS | NS | NS | NS |
| CV (%) | | 2.60 | 2.99 | 2.77 | 3.13 |

*Data are presented as means of three replications ± standard errors. NS = non-significant (p > 0.05). CV = coefficient of variation (%)*

## 3.2 Electrical Conductivity

Soil electrical conductivity (EC) differed significantly among cropping systems at the 0-15 cm depth in both years ($p$ = 0.03 in 2023-24 and $p$ = 0.02 in 2024-25), while at the 15-30 cm depth the differences were non-significant in both years (Table 2). At the 0-15 cm depth, the highest EC was recorded under basmati rice-potato-maize in both years (0.22 dS $m^{-1}$ in 2023-24 and 0.24 dS $m^{-1}$ in 2024-25). However, these values were statistically at par with those of all other cropping systems, except sorghum-berseem-pearl millet, which recorded significantly lower EC values. At the 15-30 cm depth, EC ranged from 0.20 dS $m^{-1}$ under the black gram-gram-*Sesbania* system to 0.24 dS $m^{-1}$ under the basmati rice-potato-maize system. The relatively higher EC observed in cereal-based systems may be due to higher fertilizer application rates, which may have increased the concentration of soluble salts in the soil compared with legume-based systems. Kumar et al. (2025) observed higher EC in cereal-based systems compared with vegetable-based systems.

**Table 2. Effect of diversified cropping systems on soil electrical conductivity (EC) at 0-15 cm and 15-30 cm depths**

| Treatment | Cropping Systems | EC (dS $m^{-1}$) | | | |
|---|---|---|---|---|---|
| | | 0-15 cm | | 15-30 cm | |
| | | 2023-24 | 2024-25 | 2023-24 | 2024-25 |
| $T_1$ | Rice-Wheat-Fallow | 0.22±0.002ab | 0.22±0.012ab | 0.23±0.007 | 0.22±0.012 |
| $T_2$ | Rice-Lentil-Cowpea | 0.20±0.003ab | 0.21±0.007ab | 0.21±0.015 | 0.21±0.009 |
| $T_3$ | Basmati Rice-Potato-Maize | 0.22±0.003a | 0.24±0.006a | 0.23±0.009 | 0.24±0.009 |
| $T_4$ | Sweet Corn-Broccoli-Okra | 0.22±0.003ab | 0.23±0.004ab | 0.22±0.013 | 0.23±0.010 |
| $T_5$ | Soybean-Wheat-Cowpea | 0.20±0.003ab | 0.20±0.008ab | 0.22±0.003 | 0.22±0.007 |
| $T_6$ | Maize-Barley-Cowpea | 0.21±0.008ab | 0.22±0.004ab | 0.23±0.019 | 0.23±0.012 |
| $T_7$ | Sorghum-Berseem-Pearl millet | 0.21±0.004ab | 0.22±0.011ab | 0.22±0.006 | 0.22±0.014 |
| $T_8$ | Black gram-Gram-*Sesbania* | 0.20±0.004b | 0.20±0.004b | 0.20±0.005 | 0.20±0.004 |
| *p*-value | | 0.03 | 0.02 | NS | NS |
| CV (%) | | 3.79 | 6.26 | 8.84 | 6.79 |

*Data are presented as means of three replications ± standard errors. Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means according to Tukey's HSD test at p ≤ 0.05. The letter 'a' denotes the highest mean group; NS = non-significant (p > 0.05). CV = coefficient of variation (%)*

## 3.3 Bulk Density

Soil bulk density (BD) differed significantly among cropping systems at the 0-15 cm depth in both years ($p$ = 0.02), while at the 15-30 cm depth the differences were non-significant in both years (Table 3). At the 0-15 cm depth, rice-wheat-fallow recorded the highest BD in both years (1.34 Mg $m^{-3}$ in 2023-24 and 1.35 Mg $m^{-3}$ in 2024-25). However, these values were statistically at par with those of most other cropping systems, except the maize-barley-cowpea system, which recorded significantly lower BD at this depth in both years (1.30 Mg $m^{-3}$). At the 15-30 cm depth, BD ranged from 1.31 Mg $m^{-3}$ under maize-barley-cowpea to 1.36 Mg $m^{-3}$ under rice-wheat-fallow. The lower BD observed under maize-barley-cowpea at the 0-15 cm depth may be due to the inclusion of a legume component in the system. Legume crops enhance soil aggregation through greater rhizodeposition, root biomass, and organic matter inputs, which improve soil structure and increase pore space, thereby reducing soil BD (Nath et al., 2023). In contrast, the higher BD observed under cereal-based systems reflects gradual deterioration of soil structure due to puddling and limited organic matter return, which together reduce aggregate stability and macroporosity, thereby increasing BD (Deng et al., 2014).

**Table 3. Effect of diversified cropping systems on soil bulk density (BD) at 0-15 cm and 15-30 cm depths**

| Treatment | Cropping Systems | BD (Mg $m^{-3}$) | | | |
|---|---|---|---|---|---|
| | | 0-15 cm | | 15-30 cm | |
| | | 2023-24 | 2024-25 | 2023-24 | 2024-25 |
| $T_1$ | Rice-Wheat-Fallow | 1.34±0.002a | 1.35±0.005a | 1.35±0.006 | 1.36±0.004 |
| $T_2$ | Rice-Lentil-Cowpea | 1.32±0.009ab | 1.31±0.003ab | 1.33±0.012 | 1.32±0.011 |
| $T_3$ | Basmati Rice-Potato-Maize | 1.32±0.009ab | 1.34±0.003ab | 1.33±0.018 | 1.35±0.035 |
| $T_4$ | Sweet Corn-Broccoli-Okra | 1.32±0.004ab | 1.33±0.020ab | 1.34±0.014 | 1.34±0.024 |

| Treatment | Cropping Systems | BD (Mg m$^{-3}$) | | | |
|---|---|---|---|---|---|
| | | 0-15 cm | | 15-30 cm | |
| | | 2023-24 | 2024-25 | 2023-24 | 2024-25 |
| $T_5$ | Soybean-Wheat-Cowpea | 1.33±0.004ab | 1.32±0.005ab | 1.34±0.017 | 1.33±0.041 |
| $T_6$ | Maize-Barley-Cowpea | 1.30±0.007b | 1.30±0.006b | 1.31±0.016 | 1.32±0.008 |
| $T_7$ | Sorghum-Berseem-Pearl millet | 1.34±0.011a | 1.32±0.011ab | 1.36±0.023 | 1.35±0.022 |
| $T_8$ | Black gram-Gram-*Sesbania* | 1.32±0.011ab | 1.31±0.011ab | 1.33±0.022 | 1.32±0.006 |
| *p*-value | | 0.02 | 0.02 | NS | NS |
| CV (%) | | 0.98 | 1.30 | 2.26 | 3.02 |

*Data are presented as means of three replications ± standard errors. Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means according to Tukey's HSD test at p ≤ 0.05. The letter 'a' denotes the highest mean group; NS = non-significant (p > 0.05). CV = coefficient of variation (%)*

### 3.4 Water Holding Capacity

Water holding capacity (WHC) showed significant differences among cropping systems across depths and years of the study (Table 4). At the 0-15 cm depth, black gram-gram-*Sesbania* recorded the highest WHC (54.42%) in 2023-24, whereas rice-lentil-cowpea recorded the highest WHC (58.88%) in 2024-25. However, these values were statistically at par with most cropping systems. At the 15-30 cm depth, black gram-gram-*Sesbania* recorded the highest WHC in both years, with values of 50.51% in 2023-24 and 53.71% in 2024-25. However, in 2024-25, this value was at par with that of rice-lentil-cowpea (52.83%). The inclusion of legumes in the cropping systems progressively increased WHC at both soil depths over the two-year study period. Similar improvements in soil water holding capacity under legume-based cropping systems have been reported by Singh et al. (2020) and Nath et al. (2023). This may be due to improved soil structure and reduced BD resulting from the inclusion of legumes or green manures (Boparai et al., 1992). Legumes increase soil organic carbon, thereby enhancing the soil's capacity to retain soil moisture (Nath et al., 2023). In contrast, continuous cereal cropping is often associated with subsurface compaction caused by intensive tillage, which reduces macroporosity, and is further compounded by limited organic matter inputs, thereby reducing soil water holding capacity (Abshiba et al., 2025).

**Table 4. Effect of diversified cropping systems on soil water holding capacity (WHC) at 0-15 cm and 15-30 cm depths**

| Treatment | Cropping Systems | WHC (%) | | | |
|---|---|---|---|---|---|
| | | 0-15 cm | | 15-30 cm | |
| | | 2023-24 | 2024-25 | 2023-24 | 2024-25 |
| $T_1$ | Rice-Wheat-Fallow | 46.28±0.64ab | 47.44±2.01b | 42.71±1.77ab | 41.68±2.31c |
| $T_2$ | Rice-Lentil-Cowpea | 51.86±1.60ab | 58.88±1.38a | 49.21±0.93ab | 52.83±0.92a |
| $T_3$ | Basmati Rice-Potato-Maize | 48.41±1.68ab | 45.67±2.33b | 42.47±1.11ab | 40.97±0.92c |
| $T_4$ | Sweet Corn-Broccoli-Okra | 46.89±2.64ab | 51.19±3.23ab | 41.64±2.86b | 40.74±0.57c |
| $T_5$ | Soybean-Wheat-Cowpea | 49.53±1.28ab | 50.37±2.05ab | 48.31±1.92ab | 50.74±1.01ab |
| $T_6$ | Maize-Barley-Cowpea | 45.50±0.74b | 51.10±1.48ab | 43.76±1.44ab | 44.16±1.64bc |
| $T_7$ | Sorghum-Berseem-Pearl millet | 46.47±1.27ab | 50.87±1.26ab | 44.01±1.99ab | 46.67±0.42abc |
| $T_8$ | Black gram-Gram-*Sesbania* | 54.42±2.45a | 54.99±2.23ab | 50.51±1.09a | 53.71±2.44a |
| *p*-value | | 0.03 | 0.02 | 0.01 | 0.01 |
| CV (%) | | 6.18 | 7.48 | 7.19 | 5.77 |

*Data are presented as means of three replications ± standard errors. Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means according to Tukey's HSD test at p ≤ 0.05. The letter 'a' denotes the highest mean group; NS = non-significant (p > 0.05). CV = coefficient of variation (%)*

### 3.5 Yield Sustainability Index

The Yield Sustainability Index (YSI) differed significantly among the cropping systems during both years of the study ($p < 0.01$) (Table 5). Among the cropping systems, sweet corn-broccoli-okra exhibited the highest mean YSI in both years (4.32 in 2023-24 and 4.59 in 2024-25), indicating the highest yield sustainability, followed by basmati rice-potato-maize (3.04 and 2.68) and sorghum-berseem-pearl millet (1.83 and 1.60). Compared with the rice-wheat-fallow system, the sweet corn-broccoli-okra system recorded 254% higher YSI in 2023-24 and 350% higher YSI in 2024-25. Similar findings were reported by Nath et al. (2023), who found that crop diversification through legume inclusion increased the Sustainable Yield Index compared with cereal-cereal cropping systems. Likewise, Meena et al. (2026) reported that sustainable farming practices, including conservation agriculture, integrated nutrient management, and optimum irrigation, significantly improved YSI.

**Table 5. Effect of diversified cropping systems on yield sustainability index (YSI)**

| Treatment | Cropping Systems | YSI | |
|---|---|---|---|
| | | 2023-24 | 2024-25 |
| $T_1$ | Rice-Wheat-Fallow | 1.22±0.008de | 1.02±0.015e |
| $T_2$ | Rice-Lentil-Cowpea | 1.35±0.037d | 1.30±0.014d |
| $T_3$ | Basmati Rice-Potato-Maize | 3.04±0.059b | 2.68±0.046b |
| $T_4$ | Sweet corn-Broccoli-Okra | 4.32±0.091a | 4.59±0.088a |
| $T_5$ | Soybean-Wheat-Cowpea | 1.32±0.019d | 1.17±0.004de |
| $T_6$ | Maize-Barley-Cowpea | 1.34±0.021d | 1.15±0.009de |
| $T_7$ | Sorghum-Berseem-Pearl millet | 1.83±0.090c | 1.60±0.061c |
| $T_8$ | Black gram-Gram-*Sesbania* | 1.00±0.002e | 1.00±0.003e |
| *p*-value | | <0.01 | <0.01 |
| CV (%) | | 4.77 | 4.24 |

*Data are presented as means of three replications ± standard errors. Treatments sharing the same letter were not significantly different, while different letters indicate significant differences in treatment means according to Tukey's HSD test at p ≤ 0.05. The letter 'a' denotes the highest mean group. CV = coefficient of variation (%)*

## 4. Conclusion

The two-year study demonstrated that diversified cropping systems significantly influenced YSI and several soil physicochemical properties, particularly at the 0-15 cm soil depth. Sweet corn-broccoli-okra consistently recorded the highest YSI in both years, indicating that it provided the most stable yields among the cropping systems evaluated. With respect to soil properties, pH remained statistically unaffected by the cropping systems at both depths and in both years. In contrast, EC and BD showed significant differences among cropping systems at the 0-15 cm depth during both years of the study. Cereal-dominant systems, such as rice-wheat-fallow and basmati rice-potato-maize, showed higher EC and BD, whereas legume-inclusive systems, such as maize-barley-cowpea, demonstrated comparatively lower BD. WHC improved progressively under legume- and green manure-based systems over the two-year study period, particularly under black gram-gram-*Sesbania* and rice-lentil-cowpea, indicating gradual improvement in soil water retention. Overall, the findings indicate that high-value cereal-vegetable systems, such as sweet corn-broccoli-okra, can enhance yield sustainability, whereas legume- and green manure-based systems can improve soil physical properties. Therefore, crop diversification through the inclusion of high-value crops, legumes, and green manures can improve productivity while maintaining soil quality in the *Tarai* region of the Indo-Gangetic Plains.

## 5. Limitations

The study was conducted for only two years at a single location in the *Tarai* region; therefore, the findings represent short-term responses under the specific soil and climatic conditions of Pantnagar. Only selected soil physical and chemical properties were assessed. Long-term, multi-location studies including biological, nutrient, and economic indicators would strengthen the evaluation of diversified cropping systems.

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## 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 in the writing or editing of this manuscript.

## Competing Interests

Authors have declared that no competing interests exist.

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