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# Comparative Analysis of Tillage Practices on Soil Characteristics in *Vertisol* for Groundnut-based Cropping System

**Meti Ranjitha [a++*], S. T. Hundekar [b#], Basavaraj S Yenagi [c†], Jakir Hussain K. N. [a++] and Mahalaxmi Shrishail Devarnavadgi [a++]**

[a] *Department of Soil Science and Agricultural Chemistry, College of Agriculture, UAS, Dharwad-580005, Karnataka, India.*
[b] *AICRP on Agroforestry, MARS, UAS, Dharwad-580005, Karnataka, India.*
[c] *AICRP on Groundnut, MARS, UAS, Dharwad- 580005, Karnataka, India.*

***Authors' contributions***

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

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[++] *Ph.D. Scholar;*
[#] *Senior Scientist (Soil Science);*
[†] *Associate Professor;*
**Corresponding author: E-mail: ranjumetiranju@gmail.com;*

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## ABSTRACT

Tillage practices in groundnut-based *Vertisol* systems is essential for improving soil health and maximizing agricultural productivity. This study investigates the impact of tillage practices and cropping systems on soil physical and chemical properties in the *Vertisol* region of Karnataka during the 2022-23 *Kharif* and *Rabi* seasons. Conducted at the MARS, UAS, Dharwad, the experiment utilized a strip plot design, comparing minimum tillage with crop residue incorporation (M1) and conventional tillage without residue (M2) across four cropping systems. Findings revealed that minimum tillage significantly enhanced soil properties, demonstrating improved porosity (52.14%), maximum water holding capacity (55.97%) and soil aggregate stability (62.42%) while reducing bulk density (1.27 Mg $m^{-3}$) at the surface layer. Among cropping systems, the groundnut + pigeon pea combination showed superior soil characteristics, with porosity at 50.88%, MWHC at 55.05%, and reduced bulk density of 1.31 Mg $m^{-3}$ at 0-15 cm depth. Additionally, minimum tillage led to higher soil organic carbon (7.65 g $kg^{-1}$) and available NPK levels (315.8 kg $ha^{-1}$ N, 44.06 kg $ha^{-1}$ P, 324.53 kg $ha^{-1}$ K), particularly in the groundnut + pigeon pea system. These findings emphasize the efficacy of conservation agriculture techniques, reinforcing existing research that highlights how minimum tillage and leguminous cropping systems enhance soil health and foster sustainable farming practices. Such results are pivotal for promoting sustainable agricultural development, as they illustrate that implementing these practices can lead to significant improvements in soil vitality, crucial for boosting crop yields and ensuring ecological stability in Karnataka's *Vertisol* region.

*Keywords: Minimum tillage; conventional tillage; cropping systems; groundnut; Vertisol.*

## 1. INTRODUCTION

Groundnut (*Arachis hypogaea*), a key oilseed crop contributing significantly to India's agricultural economy, faces production challenges in Karnataka due to poor soil health and inadequate tillage practices. Groundnut seeds are rich in oil (50%), protein (25-30%), carbohydrates (20%) and fiber (5%). However, declining soil fertility, aggravated by conventional tillage, disrupts soil structure, compacts the soil, and reduces moisture retention (Lenka and Lenka, 2014). This has emphasized sustainable soil management practices, particularly the shift from conventional to conservation tillage or no-till systems (Giller et al., 2015). Conservation tillage enhances soil organic matter, promotes better water infiltration and improves bulk density, improving soil health and increasing crop yields (Derpsch and Friedrich, 2009).

In India, conservation tillage practices in *Vertisol* under groundnut-based systems have shown significant benefits. Studies reveal that conservation tillage boosts soil organic carbon by 12-15% and increases groundnut yields by 8-10% compared to conventional tillage systems (Sharma et al., 2019). Cropping systems that integrate residue management, cover crops, and reduced tillage further enhance soil fertility and structure, leading to long-term sustainability (Singh et al., 2014 and Rusu et al., 2015). The practice of different tillage methods plays a crucial role in shaping soil structure and nutrient distribution. Minimum tillage with residue incorporation and conventional tillage without residue retention have distinct impacts (Franzluebbers et al., 1996). Minimum tillage, especially with crop residue incorporation, often results in vertical stratification of soil organic carbon (SOC) and other nutrients, which can limit deep-root nutrient access and potentially restrict the growth of crops with deeper root systems (Mrabet et al., 2001 and Tangyuan et al., 2009). While these practices enhance soil moisture retention and reduce erosion, they can also pose challenges to nutrient availability in lower soil layers (Lal, 2004). Groundnut, occupying around 4.7 million hectares in India, thrives under these optimized practices, ensuring improved productivity and resilience, particularly in semi-arid regions like Karnataka. These practices are vital to overcoming soil degradation, maximizing water use efficiency, and maintaining the long-term viability of groundnut cultivation in challenging environments (Dyck et al*.,* 2016).

## 2. MATERIALS AND METHODS

### 2.1 Experimental Site

The field experiment at the Main Agricultural Research Station (MARS) in Dharwad, conducted during the *Kharif* and *Rabi* seasons of 2022-2023, is part of an ongoing study initiated in 2020. Situated in the Northern Transition Zone of

Karnataka, this site stands at 678 meters' elevation. It receives an average annual rainfall of 799.23 mm, with 901.6 mm recorded during the experimental year, peaking in October and September. The highest temperature was 36.4°C in April 2023, and the lowest was 26.6°C in July 2022, with relative humidity reaching 87.4% in July. The soil, characterized as shallow black clay, typical of *Vertisol*, showed consistent clay texture in initial assessments.

Minimum tillage plots demonstrated a lower bulk density (1.28 Mg $m^{-3}$) compared to conventional tillage plots (1.36 Mg $m^{-3}$), leading to enhanced porosity (51.9% vs. 47.9%) and greater water-holding capacity (55.3% and 52.5%). Soil aggregate stability was also higher in minimum tillage (62.3%) than in conventional systems (60.6%). Chemically, both plots had similar pH levels (around 7.5) and electrical conductivity, but minimum tillage plots had significantly higher levels of soil organic carbon (7.1 g $kg^{-1}$) and available nutrients, including nitrogen (295.2 kg $ha^{-1}$), phosphorus (40.2 kg $ha^{-1}$), and potassium (315.3 kg $ha^{-1}$), compared to lower values in conventional tillage plots.

## 2.2 Experimental Details

The study utilized a **strip plot design (SPD)** with four replications to assess the effects of different tillage systems and cropping patterns on groundnut production. Each gross plot measured **4.8 m x 4.0 m**, while the net plot size was **4.2 m x 3.6 m**. The layout of the experiment was meticulously planned, ensuring proper allocation of treatments across the designated plots.

**Treatments:**

Main Plot Treatments:

1. **M1**: Minimum tillage with incorporation of previous year's crop residue, employing practices such as cultivator use and harrowing.
2. **M2**: Conventional tillage without incorporation of crop residue, which involved deep ploughing, cultivator use, and harrowing.

Sub-Plot Treatments (Cropping Systems):

1. **S1**: Groundnut + Cotton (4:2)
2. **S2**: Groundnut + Pigeon Pea (4:2)
3. **S3**: Groundnut + Chilli (4:2)
4. **S4**: Groundnut – Wheat

Fertilizer Application: The recommended dose of fertilizers (RDF) was applied according to the guidelines from the **University of Agricultural Sciences, Dharwad**, tailored for Zone 8. Fertilizers were applied in the following formulations:

- Urea, Diammonium Phosphate (DAP), Muriate of Potash (MOP) and Zinc Sulphate ($ZnSO_4$)

**List 1. Treatment combinations**

| Treatment | Details | Notation |
|---|---|---|
| **T1** | Minimum tillage with incorporation of crop residue and Groundnut + Cotton (4:2) | M1S1 |
| **T2** | Minimum tillage with incorporation of crop residue and Groundnut + Pigeon Pea (4:2) | M1S2 |
| **T3** | Minimum tillage with incorporation of crop residue and Groundnut + Chilli (4:2) | M1S3 |
| **T4** | Minimum tillage with incorporation of crop residue and Groundnut – Wheat | M1S4 |
| **T5** | Conventional tillage without incorporation of crop residue and Groundnut + Cotton (4:2) | M2S1 |
| **T6** | Conventional tillage without incorporation of crop residue and Groundnut + Pigeon Pea (4:2) | M2S2 |
| **T7** | Conventional tillage without incorporation of crop residue and Groundnut + Chilli (4:2) | M2S3 |
| **T8** | Conventional tillage without incorporation of crop residue and Groundnut – Wheat | M2S4 |

**List 2. The specific fertilizer dosages for each crop were as follows**

| Crop | N (kg $ha^{-1}$) | $P_2O_5$ (kg $ha^{-1}$) | $K_2O$ (kg $ha^{-1}$) | $ZnSO_4$ (kg $ha^{-1}$) |
|---|---|---|---|---|
| Groundnut (sole) | 25 | 50 | 25 | 0 |
| Groundnut (Intercrop) | 13.4 | 25.4 | 13.4 | 0 |
| Cotton | 79 | 40 | 40 | 0 |
| Pigeon Pea | 25 | 50 | 80 | 15 |
| Chilli | 45 | 49.5 | 49.5 | 0 |
| Wheat | 40 | 30 | 20 | 8 |

This structured methodology ensured a comprehensive evaluation of the impact of tillage practices and cropping systems on soil health, crop yield, and nutrient dynamics within the experimental site.

### 2.3 Soil Sampling and Laboratory Analysis

Soil samples were collected from the experimental field at two depths (0-15 cm) following the completion of the experiment, specifically after the harvest of both *Kharif* and *Rabi* crops. These samples were then analyzed in the laboratory to determine various soil properties, including soil organic carbon (SOC), nitrogen (N), phosphorus (P), and potassium (K), using standard analytical procedures. The SOC was assessed through the Walkley and Black wet oxidation method as outlined by Sparks (1996). Nitrogen content was measured using the micro-Kjeldahl method, while available phosphorus was quantified via the Olsen method, and exchangeable potassium was extracted using the NH4OAC method. Bulk density (BD) of the soil was measured using the clod method described by Black (1965). Soil porosity was calculated based on the relationship between bulk density and particle density (PD). The maximum water holding capacity (MWHC) was determined using the Keen-Raczkowski brass cup method as per Piper (1966). Additionally, soil aggregate stability was evaluated using the wet sieving method established by Yoder and Robert (1936).

### 2.4 Statistical Analysis of Data

The data obtained from the experiment on various characters was subjected to statistical analysis as per the analysis of variance (ANOVA) technique for ***Strip Plot Design*** as described by Gomez and Gomez (1984). The significances level used in ‘F’ test was P = 0.05 and critical difference (CD) values were calculated where ‘F’ test was found significant.

## 3. RESULTS AND DISCUSSION

The study revealed notable differences in soil bulk density (BD) and porosity between two tillage practices and four cropping systems at both 0-15 cm and 15-30 cm depths, with minimum tillage (M1) consistently showing lower BD and higher porosity compared to conventional tillage (M2) (Table 1). For example, at the 0-15 cm depth, the bulk density under minimum tillage ranged from 1.26 to 1.29 Mg $m^{-3}$, while conventional tillage ranged from 1.37 to 1.40 Mg $m^{-3}$. This finding aligns with previous research indicating that minimum tillage enhances soil aeration and water infiltration, ultimately improving soil porosity (Singh et al., 2014; Lal and Kimble., 1997). Specifically, the porosity for minimum tillage was significantly higher (51.57% to 52.70%) than for conventional tillage (46.17% to 49.06%), facilitating better root penetration and nutrient uptake, which can contribute to higher crop yields (Franzluebbers and Hons, 1996). Additionally, the cropping systems incorporating legumes, such as groundnut + pigeon pea and groundnut + chilli, exhibited superior soil properties, with the lowest BD (1.31 Mg $m^{-3}$) and the highest porosity (50.88%) compared to non-leguminous systems like groundnut + cotton and groundnut - wheat, which had higher BD and lower porosity values. This enhancement in soil characteristics is attributed to the legumes' ability to increase organic carbon content and biomass production, thereby improving soil structure (Ishaq et al., 2001; Mrabet et al., 2001). The study highlights critical role of adopting sustainable agricultural practices, particularly conservation agriculture, to enhance soil health and crop productivity, especially in clayey soils like those found in Karnataka's *Vertisol* region. The results emphasize the positive influence of minimum tillage and leguminous cropping systems on soil physical properties, supporting findings from other studies that advocate for these practices as beneficial for sustainable agriculture (Malhi et al., 2006).

The results revealed significant differences in soil aggregate stability and maximum water holding capacity (MWHC) influenced by tillage practices and cropping systems at varying soil depths. Specifically, at the 0-15 cm depth, minimum tillage (M1) exhibited higher aggregate stability (62.42%) and MWHC (55.97%) compared to conventional tillage (M2), which had values of 60.52% and 52.15%, respectively (Table 2). This enhancement in M1 can be attributed to the protective effect of crop residues, which improve soil organic carbon content and aggregate formation by mitigating the impact of raindrops and promoting stable soil structures (Hudson, 1994; Bronick and Lal, 2005). The conventional tillage method disrupted soil aggregates each time it was tilled, resulting in lower soil health and function. Among cropping systems, the groundnut + pigeon pea combination demonstrated the highest MWHC (55.05%),

**Table 1. Effect of tillage practices and cropping systems on soil bulk density and porosity at surface and subsurface soil depths**

| | Bulk density of soil (Mg $m^{-3}$) | | | | | | | Porosity of soil (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | | **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | |
| | **Tillage practices** | | | **Tillage practices** | | | | **Tillage practices** | | | **Tillage practices** | | |
| | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** | | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** |
| **$S_1$** | 1.27 | 1.37 | 1.32 | 1.35 | 1.41 | 1.38 | **$S_1$** | 52.33 | 48.80 | 50.56 | 51.85 | 47.80 | 49.83 |
| **$S_2$** | 1.26 | 1.35 | 1.31 | 1.32 | 1.39 | 1.36 | **$S_2$** | 52.70 | 49.06 | 50.88 | 52.03 | 48.90 | 50.47 |
| **$S_3$** | 1.28 | 1.39 | 1.33 | 1.36 | 1.43 | 1.40 | **$S_3$** | 51.95 | 47.55 | 49.75 | 51.20 | 47.30 | 49.25 |
| **$S_4$** | 1.29 | 1.40 | 1.34 | 1.38 | 1.48 | 1.43 | **$S_4$** | 51.57 | 46.17 | 48.87 | 51.01 | 47.00 | 49.01 |
| **Mean** | 1.27 | 1.38 | | 1.35 | 1.43 | | **Mean** | 52.14 | 47.89 | | 51.52 | 47.75 | |
| | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | | | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | |
| **M** | 0.011 | 0.050 | | 0.017 | NS | | **M** | 0.63 | 2.85 | | 0.85 | NS | |
| **S** | 0.007 | 0.023 | | 0.027 | NS | | **S** | 0.44 | 1.42 | | 1.14 | NS | |
| **M×S** | 0.014 | NS | | 0.047 | NS | | **M×S** | 0.93 | NS | | 1.82 | NS | |

*Main plots (Tillage practices)*
*$M_1$: Minimum tillage with incorporation of previous year crop residue*
*$M_2$: Conventional tillage without incorporation of crop residue*

*Sub plots (Cropping systems CS)*
*$S_1$: Groundnut + Cotton*
*$S_2$: Groundnut + Pigeon pea*
*$S_3$: Groundnut + Chilli*
*$S_4$: Groundnut – Wheat*

**Table 2. Effect of tillage practices and cropping systems on soil aggregate stability and maximum water holding capacity of soil at surface and subsurface soil depths**

| | Soil aggregate stability (%) | | | | | | | Maximum water holding capacity (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | | **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | |
| | **Tillage practices** | | | **Tillage practices** | | | | **Tillage practices** | | | **Tillage practices** | | |
| | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** | | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** |
| **$S_1$** | 62.45 | 60.55 | 61.50 | 61.32 | 59.90 | 60.61 | **$S_1$** | 56.20 | 52.60 | 54.40 | 55.80 | 51.80 | 53.80 |
| **$S_2$** | 62.48 | 60.56 | 61.52 | 61.40 | 60.10 | 60.75 | **$S_2$** | 56.90 | 53.20 | 55.05 | 56.20 | 52.40 | 54.30 |
| **$S_3$** | 62.40 | 60.49 | 61.44 | 60.90 | 59.80 | 60.35 | **$S_3$** | 55.60 | 51.80 | 53.70 | 55.10 | 51.30 | 53.20 |
| **$S_4$** | 62.37 | 60.48 | 61.42 | 60.43 | 59.60 | 60.02 | **$S_4$** | 55.20 | 51.00 | 53.10 | 54.70 | 49.80 | 52.25 |
| **Mean** | 62.42 | 60.52 | | 61.01 | 59.85 | | **Mean** | 55.97 | 52.15 | | 55.45 | 51.33 | |
| | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | | | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | |
| **M** | 0.40 | 1.79 | | 0.76 | NS | | **M** | 0.44 | 1.96 | | 0.69 | NS | |
| **S** | 0.70 | NS | | 1.20 | NS | | **S** | 0.34 | 1.09 | | 1.07 | NS | |
| **M×S** | 1.67 | NS | | 2.04 | NS | | **M×S** | 1.15 | NS | | 1.81 | NS | |

*Main plots (Tillage practices)*
*$M_1$: Minimum tillage with incorporation of previous year crop residue*
*$M_2$: Conventional tillage without incorporation of crop residue*

*Sub plots (Cropping systems CS)*
*$S_1$: Groundnut + Cotton*
*$S_2$: Groundnut + Pigeon pea*
*$S_3$: Groundnut + Chilli*
*$S_4$: Groundnut – Wheat*

**Table 3. Effect of tillage practices and cropping systems on soil organic carbon and available nitrogen in soil at surface and subsurface soil depths**

| | Soil organic carbon (g kg$^{-1}$) | | | | | | | Soil available nitrogen (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | | **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | |
| | **Tillage practices** | | | **Tillage practices** | | | | **Tillage practices** | | | **Tillage practices** | | |
| | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** | | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** |
| **$S_1$** | 7.80 | 4.50 | 6.15 | 5.20 | 3.40 | 4.30 | **$S_1$** | 310.2 | 270.0 | 290.1 | 241.8 | 190.0 | 215.9 |
| **$S_2$** | 8.00 | 4.60 | 6.30 | 5.40 | 3.50 | 4.45 | **$S_2$** | 328.5 | 285.1 | 306.8 | 257.5 | 204.9 | 231.2 |
| **$S_3$** | 7.41 | 4.26 | 5.83 | 5.30 | 3.30 | 4.30 | **$S_3$** | 318.4 | 276.3 | 297.4 | 250.6 | 193.6 | 222.1 |
| **$S_4$** | 7.40 | 4.25 | 5.83 | 5.30 | 3.15 | 4.23 | **$S_4$** | 306.1 | 268.4 | 287.3 | 235.7 | 180.4 | 208.1 |
| **Mean** | 7.65 | 4.40 | | 5.30 | 3.34 | | **Mean** | 315.8 | 275.0 | | 246.4 | 192.2 | |
| | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | | | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | |
| **M** | 0.12 | 0.52 | | 0.07 | 0.32 | | M | 3.25 | 14.62 | | 3.12 | 14.03 | |
| **S** | 0.10 | 0.31 | | 0.09 | NS | | S | 3.49 | 11.17 | | 4.51 | 14.44 | |
| **M×S** | 0.14 | NS | | 0.15 | NS | | M×S | 8.24 | NS | | 7.57 | NS | |

*Main plots (Tillage practices)*
*$M_1$: Minimum tillage with incorporation of previous year crop residue*
*$M_2$: Conventional tillage without incorporation of crop residue*

*Sub plots (Cropping systems CS)*
*$S_1$: Groundnut + Cotton*
*$S_2$: Groundnut + Pigeon pea*
*$S_3$: Groundnut + Chilli*
*$S_4$: Groundnut - Wheat*

**Table 4. Effect of tillage practices and cropping systems on soil available phosphorus and potassium at surface and subsurface soil depths**

| | Soil available phosphorus ($P_2O_5$ kg $ha^{-1}$) | | | | | | | Soil available potassium ($K_2O$ kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | | **CS** | **0-15 cm depth** | | | **15-30 cm depth** | | |
| | **Tillage practices** | | | **Tillage practices** | | | | **Tillage practices** | | | **Tillage practices** | | |
| | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** | | **$M_1$** | **$M_2$** | **Mean** | **$M_1$** | **$M_2$** | **Mean** |
| **$S_1$** | 43.50 | 36.41 | 39.95 | 34.20 | 27.50 | 30.85 | **$S_1$** | 316.1 | 315.2 | 315.6 | 278.5 | 268.3 | 273.4 |
| **$S_2$** | 46.12 | 40.57 | 43.35 | 36.80 | 30.62 | 33.71 | **$S_2$** | 336.0 | 314.1 | 325.1 | 285.2 | 272.1 | 278.7 |
| **$S_3$** | 44.26 | 38.66 | 41.46 | 37.50 | 29.47 | 33.48 | **$S_3$** | 331.2 | 302.8 | 317.0 | 290.3 | 258.4 | 274.4 |
| **$S_4$** | 42.36 | 32.16 | 37.26 | 32.10 | 28.50 | 30.30 | **$S_4$** | 314.9 | 304.5 | 309.7 | 275.1 | 255.5 | 265.3 |
| **Mean** | 44.06 | 36.95 | | 35.15 | 29.02 | | **Mean** | 324.5 | 309.1 | | 282.3 | 263.6 | |
| | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | | | **SE.m±** | **CD at 5%** | | **SE.m±** | **CD at 5%** | |
| **M** | 1.29 | 5.80 | | 0.27 | 1.21 | | **M** | 2.21 | 9.94 | | 2.12 | 9.56 | |
| **S** | 0.98 | 3.15 | | 0.86 | 2.76 | | **S** | 2.61 | 8.34 | | 2.52 | 8.06 | |
| **M×S** | 2.48 | NS | | 1.23 | NS | | **M×S** | 5.64 | NS | | 6.00 | NS | |

*Main plots (Tillage practices)*
*$M_1$: Minimum tillage with incorporation of previous year crop residue*
*$M_2$: Conventional tillage without incorporation of crop residue*

*Sub plots (Cropping systems CS)*
*$S_1$: Groundnut + Cotton*
*$S_2$: Groundnut + Pigeon pea*
*$S_3$: Groundnut + Chilli*
*$S_4$: Groundnut - Wheat*

while the groundnut-wheat system recorded the lowest (53.10%), which can be explained by reduced biomass production in the latter, limiting aggregate formation and nutrient cycling (Degryze et al., 2005). No significant interaction effects were observed among cropping systems at the 15-30 cm depth, indicating that deeper soil properties may be less sensitive to the tested treatments (Sainju et al., 2007). These findings emphasize the value of conservation tillage and leguminous crops in enhancing soil properties and supporting sustainable agricultural practices, aligning with broader research advocating for practices that improve soil health and agricultural productivity (Halpern 2009; Dyck et al., 2016).

The study demonstrated that tillage practices and cropping systems significantly influenced soil organic carbon (SOC) and available nitrogen, phosphorus, and potassium (NPK) at both 0-15 cm and 15-30 cm depths. Minimum tillage (MT) exhibited markedly higher SOC (7.65 g $kg^{-1}$) and available NPK levels (315.8 kg $ha^{-1}$ for nitrogen, 44.06 kg $ha^{-1}$ for phosphorus, and 324.5 kg $ha^{-1}$ for potassium) compared to conventional tillage (CT), which recorded SOC of 4.40 g $kg^{-1}$ and lower NPK values (275.0 kg $ha^{-1}$, 36.95 kg $ha^{-1}$, and 309.1 kg $ha^{-1}$, respectively) (Tables 3 and 4). This increase in SOC in MT plots is attributed to the slower decomposition of organic residues, allowing for enhanced organic matter retention. The lower SOC in CT plots is mainly due to the loss of carbon from the soil, exacerbated by photodecomposition (Six et al., 2004 and Usman et al., 2014). The higher available NPK in MT plots is likely due to the retention of crop residues, which reduces the surface area of biomass available for microbial decomposition, thereby promoting slower decomposition and extended nutrient release over time (Bhan and Behera, 2004; Lenka et al., 2014).

Among the cropping systems, the groundnut + pigeon pea combination recorded significantly higher SOC (6.30 g $kg^{-1}$) and available NPK (306.8 kg $ha^{-1}$ for nitrogen, 43.35 kg $ha^{-1}$ for phosphorus, and 325.1 kg $ha^{-1}$ for potassium) compared to the other systems. This increase can be attributed to the exhaustive nature of cotton crops and the absence of biological nitrogen fixation in wheat during the *rabi* season, which diminishes soil nitrogen levels. The incorporation of organic residues, which contain essential plant nutrients, further enhances nutrient availability through mineralization, resulting in improved NPK levels (Buah et al., 2017; Derpsch et al., 2018). At a soil depth of 15-30 cm, CT continued to show significantly lower SOC and available NPK than MT; however, cropping systems did not influence the sub surface significantly SOC (Meena et al., 2015). Importantly, no significant interaction effects were found between tillage practices and cropping systems at both depths, indicating that the benefits of these practices on soil fertility are independent of one another (Samarendra et al., 2009 and Sharma et al. 2019).

## 4. CONCLUSION

The study demonstrates that minimum tillage (MT) practices, especially when combined with the groundnut + pigeon pea cropping system, significantly enhance soil physical and chemical properties compared to conventional tillage (CT) and other cropping systems. MT plots exhibited a marked reduction in bulk density, improved soil aggregate stability, and increased porosity by approximately 7.3%, along with a 3.6% enhancement in maximum water holding capacity (MWHC) over CT plots. Furthermore, MT practices facilitated a notable 25% increase in soil organic carbon (SOC) and available nitrogen, phosphorus, and potassium (NPK) levels at the surface soil depth, highlighting the positive impact of crop residue incorporation on soil fertility. However, it was also observed that SOC and available NPK levels decreased significantly at the 15-30 cm depth, indicating the need for continued management practices to sustain nutrient levels throughout the soil profile. The findings emphasize that adopting minimum tillage combined with leguminous cropping systems not only improves soil health and fertility but also supports long-term agricultural productivity, particularly in regions characterized by clayey soils, such as Karnataka's *Vertisol* region.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of this manuscript. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

**Details of the AI usage are given below:**

1. Small sentence correction.

## DATA AVAILABILITY STATEMENT

Data will be available upon request to the corresponding author.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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