International Journal of Plant & Soil Science

Volume 38, Issue 10, Page 362-372, 2026; Article no.IJPSS.166682
ISSN: 2320-7035

Assessing the Impact of Tillage Practices and Organic Manures on the Growth and Productivity of Cotton in Vertisols

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Authors' contributions

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

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i106354

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/166682

Original Research Article

Received: 24/07/2026
Accepted: 21/09/2026
Published: 29/09/2026

Abstract

A field experiment was conducted during Kharif 2023 at the Research Farm of the Department of Soil Science, Dr Panjabrao Deshmukh Krishi Vidyapeeth, Akola, to evaluate the effects of different tillage practices and organic manure applications on the growth and productivity of cotton cultivated in Vertisols. The experiment was laid out in a factorial randomised block design comprising four tillage treatments, namely conventional tillage, reduced tillage, minimum tillage and zero tillage, in combination with four organic manure treatments: farmyard manure at 10 t ha^{-1}, vermicompost at 5 t ha^{-1}, phosphocompost at 5 t ha^{-1} and an untreated control without manure application.Plant height, branches, squares, bolls, root characteristics, seed cotton yield, and stalk yield were evaluated. Conventional tillage generally produced the greatest plant height, reproductive growth, root development, seed cotton yield, and stalk yield, whereas zero tillage recorded the lowest values. Farmyard manure produced the greatest plant height, while phosphocompost showed favourable effects on branching, square and boll formation, root growth, and yield.

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Cite as: *Thite, M. D., Bhoyar, S. M., Konde, N. M., Jadhao, S. D., Singh, A., & Goud, V. V. (2026). Assessing the Impact of Tillage Practices and Organic Manures on the Growth and Productivity of Cotton in Vertisols. International Journal of Plant & Soil Science, 38(10), 362–372. https://doi.org/10.9734/ijpss/2026/v38i106354*

Conventional tillage produced a seed cotton yield of 14.10 q ha⁻¹ and a stalk yield of 27.78 q ha⁻¹. Among organic manure treatments, phosphocompost produced mean seed cotton and stalk yields of 11.25 and 22.07 q ha⁻¹, respectively. Significant interaction effects were observed for plant height, squares, bolls, seed cotton yield, and stalk yield, whereas interactions for branch number, root length, and root volume were non-significant. These findings demonstrate that tillage and organic manure management substantially influenced cotton performance under the Vertisol conditions evaluated.

Keywords: *Cotton; Vertisols; conventional tillage; reduced tillage; minimum tillage; zero tillage; farmyard manure; vermicompost; phosphocompost; seed cotton yield.*

1. Introduction

Cotton (*Gossypium spp*.), a name derived from the Arabic term Qutun, is one of India's major commercial crops and is widely recognised in Maharashtra as the "White Gold of Black Soil". It is the world's principal natural textile fibre and also serves as an important oilseed crop (Rajendran *et al*., 2005). The crop provides livelihoods for approximately 6 million Indian farmers and supports the employment of more than 60–70 million people involved in processing, ginning and the textile trade. India is among the leading cotton-producing countries globally, with cotton cultivated over approximately 127 lakh hectares, representing nearly 40% of the global cotton-growing area. The country produces around 302.25 lakh bales, with an average productivity of 447 kg ha⁻¹. Maharashtra has the largest area under cotton cultivation in India, covering approximately 42.22 lakh hectares, and ranks second in terms of total production. However, cotton productivity in the Vidarbha region remains considerably below the national average, at approximately 300 kg ha⁻¹. This lower productivity is attributed to several constraints, including predominantly rainfed cultivation, irregular rainfall patterns, heavy black cotton soils and inadequate access to quality agricultural inputs.Vertisols, which comprise these black cotton soils, represent a highly productive yet physically challenging resource for global agriculture. These soils are characterised by a high clay content, often ranging from 40% to over 60%, dominated by 2:1 expanding-lattice smectite or montmorillonite minerals (Dudal & Eswaran, 1988). This specific mineralogical composition imparts unique shrink-swell properties (IUSS Working Group WRB, 2015). During dry periods, Vertisols shrink profoundly, creating deep, wide surface cracks that accelerate subsurface moisture loss (Eswaran & Cook, 1988). Conversely, during monsoon or irrigation cycles, they absorb water and swell, resulting in extremely low permeability, poor aeration, and a high risk of temporary waterlogging. From a field-management perspective, Vertisols possess an exceptionally narrow workable moisture window. When wet, they become highly sticky, plastic, and unyielding, whereas when dry, they become extremely hard, cloddy, and compact.

To overcome these structural constraints and prepare an optimal seedbed for demanding cash crops such as cotton, farmers have historically resorted to heavy, intensive tillage operations. However, continuous conventional tillage severely disrupts the fragile macro-aggregates of heavy clay soils. This constant mechanical disruption breaks down soil structure, depletes organic matter through accelerated oxidation, and renders the topsoil highly vulnerable to erosion (Campbell *et al*., 2001). Furthermore, intensive tillage destroys capillary continuity within the soil matrix, which drastically reduces the soil's moisture-retention capacity and exposes the crop to severe moisture stress during mid-season dry spells. Over time, repeated heavy-machinery traffic induces subsoil compaction and creates a restrictive hardpan. This hardpan severely limits cotton root elongation, restricts access to deeper nutrient reserves, and ultimately suppresses overall vegetative and reproductive growth parameters.

This physical degradation is further compounded by modern agriculture's reliance on intensive chemical fertilisation. Although synthetic fertilisers provide an immediate increase in macronutrient availability, their continuous and exclusive use can adversely affect long-term soil fertility and health. Overapplication of chemical inputs alters soil pH, causes secondary nutrient deficiencies, and accelerates the mineralisation of native soil organic carbon. Crucially, it suppresses beneficial soil microbial biomass and enzymatic activity, which are vital for natural nutrient cycling. In Vertisols, chemically intensive farming can lead to structural crusting, reducing the soil's innate buffering capacity and locking vital nutrients into unavailable forms. Consequently, a plateau or decline in cotton productivity is often observed despite increasing fertiliser application rates.

Given these escalating ecological and economic challenges, there is an urgent need for farmers to transition towards sustainable management practices that can restore soil health without sacrificing economic yield. Optimising cotton production in Vertisols requires a dual approach: minimising physical soil disruption while simultaneously rebuilding the organic matrix of the soil profile. Conservation tillage, such as reduced or minimum tillage, offers a viable strategy to preserve soil structural integrity, mitigate moisture evaporation, and reduce operational energy costs. Conservation tillage is considered an agro-ecological practice for sustainable agriculture (Wezel *et al.*, 2014). Concurrently, the integration of organic manures acts as a structural stabiliser and a slow-release nutrient reservoir. Organic matter additions enhance macro-aggregation, increase the water-holding capacity of clay matrices, and stimulate the soil microbiome.

Recent studies have further examined the combined role of tillage and organic amendments in cotton systems, showing management-dependent changes in soil physical condition, organic matter, nutrient availability, and crop performance (Ankomah *et al.*, 2024; Kaplan, 2025). Evidence from an Indian cotton-based Vertisol also indicates that organic management can improve soil organic carbon, nitrogen status, and microbial activity, while integrated tillage-nutrient management research in another field crop reinforces the importance of evaluating these factors in combination (Lori *et al.*, 2024; Nenge *et al.*, 2025).

However, the interactive effects of varying tillage intensities combined with diverse organic manure sources within the high-clay matrix of Vertisols remain insufficiently quantified. Specifically, comprehensive data are lacking on how bulk organic sources (farmyard manure), microbially active inputs (vermicompost), and nutrient-enriched matrices (phosphocompost) perform when subjected to different mechanical tillage forces in cotton cropping systems. Filling this knowledge gap is critical for understanding how these combined management practices alter the root-zone microclimate, soil nutrient dynamics, and structural boundaries necessary for optimising resource-use efficiency and securing sustainable cotton yields.

Accordingly, the objective of the present study was to assess the effects of tillage practices and organic manure sources, individually and in combination, on the growth, root characteristics, and productivity of cotton grown on Vertisols under the study conditions.

2. Material and Methods

2.1 Experimental Site and Soil Characteristics

A field experiment was conducted during Kharif 2023 at the Research Farm of the Department of Soil Science, Dr Panjabrao Deshmukh Krishi Vidyapeeth, Akola. The experimental site was characterised by black cotton soil, classified as a Vertisol with a montmorillonitic and hyperthermic mineralogical and temperature regime. The soil was dominated by smectite clay minerals, exhibiting pronounced shrink–swell behaviour and developing deep, wide cracks in response to fluctuations in soil moisture.

2.2 Experimental Design and Treatments

The study was conducted using a factorial randomised block design (FRBD) with two experimental factors. Factor A comprised four tillage practices: T1, conventional tillage (CT); T2, reduced tillage (RT); T3, minimum tillage (MT); and T4, zero tillage (ZT). Factor B comprised four organic manure treatments: M1, farmyard manure (FYM) at 10 t ha^{-1}; M2, vermicompost (VC) at 5 t ha^{-1}; M3, phosphocompost (PC) at 5 t ha^{-1}; and M4, no manure (NM), which served as the control. Combining the four levels of each factor generated 16 treatment combinations, and each combination was replicated three times.

2.3 Biometric Observations and Plant Sampling

The biometric observations included plant height, number of branches, number of squares, and number of bolls. Five representative plants were randomly selected and tagged from the net plot area of each treatment for recording growth observations. Plant height and number of branches were recorded at 30, 60, and 90 days after sowing (DAS), whereas the numbers of squares and bolls were recorded at 60 and 90 DAS. These observations were used to evaluate the response of cotton growth and reproductive development to the tillage and organic manure treatments.

2.4 Root Characteristics

Root characteristics evaluated in the experiment comprised root length (cm) and root volume (cm^3). These variables were used to compare the responses of cotton root development across the tillage and organic manure treatments.

2.5 Yield Recording

Seed cotton was picked on a plot-wise basis. After harvesting, dry matter yield was recorded from the net plot area in all replications. Yield was calculated on a per-plot basis and subsequently expressed per hectare. The yield variables reported in the study comprised seed cotton yield and stalk yield.

2.6 Statistical Analysis

All data were statistically analysed using analysis of variance techniques (Gomez & Gomez, 1984). The factorial analysis considered the main effects of tillage practices (Factor A), organic manures (Factor B), and their interaction (A × B). Treatment comparisons were presented using the standard error of the mean [SE (m) ±] and critical difference (CD) at the 5% level, as applicable; non-significant interactions were reported as NS.

3. Results and Discussion

3.1 Plant Height

Data on the effects of tillage practices and organic manures on plant height at 30, 60, and 90 DAS are presented in Table 1.

Across all observation stages, conventional tillage produced the tallest cotton plants, recording 18.70 cm at 30 DAS, 68.03 cm at 60 DAS, and 79.25 cm at 90 DAS. Reduced tillage recorded intermediate plant heights of 14.70 cm at 30 DAS, 54.30 cm at 60 DAS, and 57.48 cm at 90 DAS and was significantly superior to T3 and T4 but remained lower than T1. Minimum tillage also showed moderately reduced heights of 14.00 cm at 30 DAS, 43.63 cm at 60 DAS, and 49.50 cm at 90 DAS; it was reported as statistically at par with T2 at 30 DAS but significantly lower at later stages. The lowest plant heights were recorded under zero tillage (T4), with values of 11.98 cm at 30 DAS, 23.13 cm at 60 DAS, and 31.00 cm at 90 DAS.

The enhanced plant height under T1 may be attributed to improved root penetration, soil aeration, and moisture availability facilitated by deeper ploughing, which supports early and sustained vegetative growth. Similar results were reported by Saleem *et al.* (2022). The reduced performance under T4 might be due to restricted root growth and lower nutrient availability resulting from poor soil loosening.

Table 1. Effect of tillage and organic inputs on plant height

Treatments	Plant height (cm)		
	30 DAS	**60 DAS**	**90 DAS**
Factor A (Tillage practices)			
T_1 – CT	18.70	68.03	79.25
T_2 – RT	14.70	54.30	57.48
T_3 – MT	14.00	43.63	49.50
T_4 – ZT	11.98	23.13	31.00
SE (m)±	**0.12**	**0.455**	**0.438**
CD @ 5%	**0.347**	**1.315**	**1.266**
Factor B (Organic manures)			
M_1 - FYM @ 10 t ha^{-1}	17.1	51.90	60.08
M_2 - VC @ 5 t ha^{-1}	15.4	48.15	55.33
M_3 - PC @ 5 t ha^{-1}	14.5	46.46	52.03
M_4 – NM	12.0	42.58	49.80
SE (m) ±	**0.12**	**0.455**	**0.438**
CD @ 5%	**0.347**	**1.315**	**1.266**
Interaction of tillage practices and organic manures (A × B)			
SE (m) ±	**0.24**	**0.91**	**0.877**
CD @ 5%	**0.694**	**2.621**	**2.532**

Plant height was significantly influenced by organic amendments across all sampling dates. FYM resulted in the highest plant heights of 17.1 cm at 30 DAS, 51.90 cm at 60 DAS, and 60.08 cm at 90 DAS and was significantly superior to all other organic inputs. Vermicompost and phosphocompost produced intermediate plant heights. M2 recorded values of 15.4 cm, 48.15 cm, and 55.33 cm at 30, 60, and 90 DAS, respectively, while M3 recorded 14.5 cm, 46.46 cm, and 52.03 cm, respectively. Both treatments significantly outperformed M4, in which no organic manure was applied. M4 consistently resulted in the shortest plants, with values of 12.0 cm, 42.58 cm, and 49.80 cm at 30, 60, and 90 DAS, respectively, indicating the important role of organic nutrient supplementation in supporting plant growth. Similar results were reported by Singh *et al.* (2020).

The interaction effect of tillage and organic inputs on cotton plant height at 30, 60, and 90 DAS is presented in Tables 2, 3, and 4, respectively. The interaction was significant at all three growth stages. Overall, the comparative analysis reveals that plant height increased steadily over time in all treatments, but the magnitude of improvement was highest under T1 and M1. These findings reinforce the importance of integrating conventional tillage with organic inputs for maximising early and sustained vegetative growth in cotton.

Table 2. Interaction effect of tillage and organic inputs on plant height of cotton (30 DAS)

Height (cm)					
Treatments	T_1 (CT)	T_2 (RT)	T_3 (MT)	T_4 (ZT)	Mean B
M_1 - FYM @ 10 t ha^{-1}	20.00	17.51	16.60	14.30	17.10
M_2 - VC @ 5 t ha^{-1}	19.07	15.77	15.30	11.80	15.48
M_3 - PC @ 5 t ha^{-1}	18.23	14.70	14.10	11.20	14.56
M_4 - No manure	16.60	10.90	10.20	10.60	12.08
Mean A	18.48	14.72	14.05	11.98	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.120	0.120	0.240		
CD @ 5 %	0.347	0.347	0.694		

Table 3. Interaction effect of tillage and organic inputs on plant height of cotton (60 DAS)

Height (cm)					
Treatments	T_1 (CT)	T_2 (RT)	T_3 (MT)	T_4 (ZT)	Mean B
M_1 - FYM @ 10 t ha^{-1}	74.80	58.70	49.00	25.10	51.90
M_2 - VC @ 5 t ha^{-1}	67.30	57.60	43.80	23.90	48.15
M_3 - PC @ 5 t ha^{-1}	65.80	54.80	42.73	22.50	46.46
M_4 - No manure	64.23	46.10	39.00	21.00	42.58
Mean A	68.03	54.30	43.63	23.13	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.455	0.455	0.910		
CD @ 5 %	1.315	1.315	2.621		

Table 4. Interaction effect of tillage and organic inputs on plant height of cotton (90 DAS)

Height (cm)					
Treatments	T_1 (CT)	T_2 (RT)	T_3 (MT)	T_4 (ZT)	Mean B
M_1 - FYM @ 10 t ha^{-1}	91.40	64.50	52.20	32.20	60.08
M_2 - VC @ 5 t ha^{-1}	78.90	60.00	50.80	31.60	55.33
M_3 - PC @ 5 t ha^{-1}	74.00	53.00	50.50	30.60	52.03
M_4 - No manure	72.70	52.40	44.50	29.60	49.80
Mean A	79.25	57.48	49.50	31.00	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.438	0.438	0.877		
CD @ 5 %	1.266	1.266	2.532		

Table 5. Effect of tillage and organic inputs on number of branches of cotton plant

Treatments	**Number of branches (plant^{-1})**		
	30 DAS	**60 DAS**	**90 DAS**
Factor A (Tillage practices)			
T_1 – CT	3.03	7.65	9.68
T_2 – RT	2.42	7.10	8.90
T_3 – MT	2.15	6.33	7.53
T_4 – ZT	1.91	3.85	4.30
SE (m)±	**0.021**	**0.042**	**0.007**
CD @ 5%	**0.06**	**0.121**	**0.021**
Factor B (Organic manures)			
M_1 - FYM @ 10 t ha^{-1}	2.36	5.95	7.35
M_2 - VC @ 5 t ha^{-1}	2.48	6.45	7.75
M_3 - PC @ 5 t ha^{-1}	2.50	7.18	8.38
M_4 – NM	2.17	5.36	6.93
SE (m) ±	**0.021**	**0.042**	**0.007**
CD @ 5%	**0.06**	**0.121**	**0.021**
Interaction of tillage practices and organic manures (A × B)			
SE (m) ±	**0.042**	**0.084**	**0.014**
CD @ 5%	**NS**	**NS**	**NS**

3.2 Number of Branches

Data on the effects of tillage and organic inputs on the number of branches at 30, 60, and 90 DAS are presented in Table 5.

At 30 DAS, the significantly highest number of branches was observed under conventional tillage (T1), with 3.03 branches per plant. This treatment significantly outperformed reduced tillage (T2), minimum tillage (T3), and zero tillage (T4). Notably, T2 (2.42) and T3 (2.15) were reported as statistically similar. The lowest branch count was consistently recorded in T4 (1.91). The difference became more pronounced at 60 DAS, with T1 registering 7.65 branches, followed by T2 and T3, while T4 remained significantly inferior (3.85). At 90 DAS, T1 maintained its superiority, with 9.68 branches per plant.

Better soil aeration and moisture conservation under conventional tillage promote axillary bud development and increased shoot biomass. Similar trends were documented by Saleem *et al.* (2022) in Vertisols, where conventional tillage resulted in greater branching due to improved soil porosity and nutrient availability.

Among the organic sources, PC (M3) consistently encouraged greater branching. At 30 DAS, the significantly highest number of branches was recorded under M3 (2.50 branches per plant), compared with FYM (M1), vermicompost (M2), and the control (M4). The trend persisted at 60 DAS (M3: 7.18) and 90 DAS (M3: 8.38), reflecting its prolonged nutrient release and microbial stimulation. Although M1 and M2 exhibited comparable effects (e.g., at 90 DAS: M1: 7.35; M2: 7.75), they performed better than the no-manure treatment (M4), which recorded the fewest branches across all stages.

The improvement in branching with organic inputs is attributed to better nutrient cycling, microbial activity, and improved soil structure. Phosphocompost likely provided more balanced nutrition, especially phosphorus, thereby enhancing apical growth and shoot differentiation. Similar results were reported by Singh *et al.* (2020).

The interaction between tillage and organic manures was statistically non-significant at 30, 60, and 90 DAS.

Table 6. Effect of tillage and organic inputs on number of squares of cotton plant

Treatments	No. of Squares (plant^{-1})	
	60 DAS	**90 DAS**
Factor A (Tillage practices)		
T_1 – CT	13.78	9.70
T_2 – RT	12.68	8.73
T_3 – MT	9.33	7.15
T_4 – ZT	4.18	3.63
SE (m)±	**0.051**	**0.085**
CD @ 5%	**0.146**	**0.244**
Factor B (Organic manures)		
M_1 - FYM @ 10 t ha^{-1}	9.78	7.15
M_2 - VC @ 5 t ha^{-1}	10.08	7.70
M_3 - PC @ 5 t ha^{-1}	12.28	8.00
M_4 – NM	7.83	6.35
SE (m) ±	**0.051**	**0.085**
CD @ 5%	**0.146**	**0.244**
Interaction of tillage practices and organic manures (A × B)		
SE (m) ±	**0.101**	**0.169**
CD @ 5%	**0.291**	**0.488**

3.3 Number of Squares

Data on the effect of tillage and organic inputs on the number of squares per cotton plant are presented in Table 6. At 60 DAS, T1 recorded 13.78 squares per plant. This value was significantly higher than those under minimum tillage (T3: 9.33) and zero tillage (T4: 4.18). A similar trend persisted at 90 DAS, when T1 again outperformed all other treatments, registering 9.70 squares per plant. Reduced tillage (T2) was reported as statistically comparable to T1 in some instances (e.g., 60 DAS: T2, 12.68). However, T4 consistently produced the fewest squares.

The positive effect of conventional tillage can be linked to better root penetration, nutrient mobilisation, and soil aeration, all of which contribute to enhanced reproductive organ formation. These results are consistent with the findings of Saleem *et al.* (2022), who reported a similar increase in square and boll numbers under conventional tillage due to improved plant vigour and timely square initiation.

Among the organic amendments, phosphocompost (M3) showed the most pronounced effect on square production. At 60 DAS, it resulted in 12.28 squares per plant, significantly exceeding FYM (M1), vermicompost (M2), and no manure (M4). At 90 DAS, M3 remained superior, with 8.00 squares per plant. FYM (M1) and vermicompost (M2) had comparable effects at 90 DAS (M1: 7.15; M2: 7.70), but phosphocompost consistently produced higher values. In contrast, the no-manure treatment (M4) consistently recorded the fewest squares (e.g., 90 DAS: 6.35).

The superior performance of phosphocompost is attributable to its rich organic matter and phosphorus availability, which promote floral induction and square retention. Similar results were reported by Singh *et al.* (2020).

The interaction effect of tillage and organic inputs on the number of squares per cotton plant at 60 and 90 DAS is presented in Tables 7 and 8, respectively. The interaction effect was statistically significant at both 60 and 90 DAS. The additive effect of improved root architecture through tillage and nutrient richness through composts leads to improved flower-bud initiation and retention, ultimately enhancing boll potential.

Table 7. Interaction effect of tillage and organic inputs on number of squares of cotton plant (60 DAS)

	Number of squares (plant^{-1})				
Treatments	**T_1 (CT)**	**T_2 (RT)**	**T_3 (MT)**	**T_4 (ZT)**	**Mean B**
M_1 - FYM @ 10 t ha^{-1}	13.40	12.30	8.90	4.50	9.78
M_2 - VC @ 5 t ha^{-1}	13.60	12.50	9.60	4.60	10.08
M_3 - PC @ 5 t ha^{-1}	17.10	16.10	11.00	4.90	12.28
M_4 - No manure	11.00	9.80	7.80	2.70	7.83
Mean A	13.78	12.68	9.33	4.18	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.051	0.051	0.101		
CD @ 5 %	0.146	0.146	0.291		

Table 8. Interaction effect of tillage and organic inputs on number of squares of cotton plant (90 DAS)

	Number of squares (plant^{-1})				
Treatments	**T_1 (CT)**	**T_2 (RT)**	**T_3 (MT)**	**T_4 (ZT)**	**Mean B**
M_1 - FYM @ 10 t ha^{-1}	9.80	8.30	7.30	3.20	7.15
M_2 - VC @ 5 t ha^{-1}	10.40	9.00	7.50	3.90	7.70
M_3 - PC @ 5 t ha^{-1}	10.50	9.60	7.60	4.30	8.00
M_4 - No manure	8.10	8.00	6.20	3.10	6.35
Mean A	9.70	8.73	7.15	3.63	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.085	0.085	0.169		
CD @ 5 %	0.244	0.244	0.488		

Table 9. Effect of tillage and organic inputs on number of bolls of cotton plant

Treatments	**No. of Bolls (plant^{-1})**	
	60 DAS	**90 DAS**
Factor A (Tillage practices)		
T_1 – CT	13.01	9.10
T_2 – RT	11.92	8.12
T_3 – MT	9.26	7.05
T_4 – ZT	4.53	3.23
SE (m)±	**0.08**	**0.07**
CD @ 5%	**0.23**	**0.21**
Factor B (Organic manures)		
M_1 - FYM @ 10 t ha^{-1}	9.49	6.90
M_2 - VC @ 5 t ha^{-1}	10.43	7.44
M_3 - PC @ 5 t ha^{-1}	11.86	7.94
M_4 – NM	6.94	5.22
SE (m) ±	**0.08**	**0.07**
CD @ 5%	**0.23**	**0.21**
Interaction of tillage practices and organic manures (A × B)		
SE (m) ±	**0.16**	**0.14**
CD @ 5%	**0.46**	**0.42**

3.4 Number of Bolls

Among the tillage treatments, CT (T1) produced the significantly highest number of bolls per plant (Table 9). At 60 DAS, T1 recorded 13.01 bolls. At 90 DAS, T1 further demonstrated its advantage by recording 9.10 bolls per plant. In contrast, zero tillage (T4) produced the fewest bolls at both stages, with 4.53 bolls per plant at 60 DAS and 3.23 at 90 DAS. Reduced tillage (T2) and minimum tillage (T3) were intermediate but were significantly inferior to conventional tillage, especially at the later stage.

The limited boll formation under zero tillage may be attributed to suboptimal root development, restricted nutrient availability, and inadequate seedbed preparation, factors that are critical during the early boll-initiation phase. These results are in line with the findings of Saleem *et al.* (2022), who reported enhanced boll retention under conventional tillage due to better soil tilth and root-zone aeration.

Phosphocompost (M3) emerged as the most effective organic source, with significantly higher boll numbers at all stages. At 60 DAS, M3 resulted in 11.86 bolls, while at 90 DAS it registered 7.94 bolls per plant. Vermicompost (M2) and FYM (M1) also performed well, although their effectiveness was slightly lower than that of phosphocompost. For instance, at 90 DAS, vermicompost recorded 7.44 bolls compared with 6.90 under FYM. Meanwhile, the no-manure treatment (M4) consistently resulted in the lowest boll numbers, recording 5.22 at 90 DAS.

These results are likely associated with the balanced nutrient profile of phosphocompost, particularly its phosphorus and organic carbon content. Phosphorus-rich composts enhance flowering and fruiting by promoting energy metabolism and hormonal regulation involved in boll initiation. Similar results were reported by Singh *et al.* (2020).

A significant interaction effect was observed between tillage and organic manure treatments at 60 and 90 DAS, as presented in Tables 10 and 11, respectively. This combination likely created a favourable rhizosphere that supported early boll setting and reduced shedding.

Table 10. Interaction effect of tillage and organic inputs on number of bolls of cotton plant (60 DAS)

	Number of bolls (plant^{-1})				
Treatments	**T_1 (CT)**	**T_2 (RT)**	**T_3 (MT)**	**T_4 (ZT)**	**Mean B**
M_1 - FYM @ 10 t ha^{-1}	12.87	11.98	9.00	4.10	9.49
M_2 - VC @ 5 t ha^{-1}	13.95	12.70	10.84	4.23	10.43
M_3 - PC @ 5 t ha^{-1}	14.30	13.95	13.20	6.00	11.86
M_4 - No manure	10.92	9.03	4.00	3.80	6.94
Mean A	13.01	11.92	9.26	4.53	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.08	0.08	0.16		
CD @ 5 %	0.23	0.23	0.46		

Table 11. Interaction effect of tillage and organic inputs on number of bolls of cotton plant (90 DAS)

	Number of bolls (plant^{-1})				
Treatments	**T_1 (CT)**	**T_2 (RT)**	**T_3 (MT)**	**T_4 (ZT)**	**Mean B**
M_1 - FYM @ 10 t ha^{-1}	8.50	8.45	7.65	3.00	6.90
M_2 - VC @ 5 t ha^{-1}	9.80	8.70	7.75	3.50	7.44
M_3 - PC @ 5 t ha^{-1}	10.60	9.10	8.00	4.07	7.94
M_4 - No manure	7.50	6.23	4.80	2.36	5.22
Mean A	9.10	8.12	7.05	3.23	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.07	0.07	0.14		
CD @ 5 %	0.21	0.21	0.42		

Table 12. Effect of tillage and organic inputs root studies

Treatments	**Root length (cm)**	**Root Volume (cm^3)**
Factor A (Tillage practices)		
T_1 – CT	15.50	58.05
T_2 – RT	14.30	56.88
T_3 – MT	14.04	56.45
T_4 – ZT	13.22	55.48
SE (m)±	**0.141**	**0.243**
CD @ 5%	**0.407**	**0.702**
Factor B (Organic manures)		
M_1 - FYM @ 10 t ha^{-1}	14.67	57.38
M_2 - VC @ 5 t ha^{-1}	14.29	56.23
M_3 - PC @ 5 t ha^{-1}	15.60	57.68
M_4 – NM	12.51	55.58
SE (m) ±	**0.141**	**0.243**
CD @ 5%	**0.407**	**0.702**
Interaction of tillage practices and organic manures (A × B)		
SE (m) ±	**0.282**	**0.487**
CD @ 5%	**NS**	**NS**

3.5 Root Length

Tillage practices significantly influenced cotton root length. Conventional tillage (T1) recorded the highest root length (15.50 cm), which was significantly superior to all other tillage treatments. Reduced tillage (T2) and minimum tillage (T3) were statistically at par with each other, while the shortest roots were observed under zero tillage (T4; 13.22 cm). Similar results were reported by Magdum (2022).

Among the organic manures, the application of phosphocompost @ 5 t ha-1 (M3) resulted in a significantly greater root length (15.60 cm) than the other treatments. This was followed by FYM @ 10 t ha-1 (M1), with a root length of 14.67 cm. The no-manure treatment (M4) recorded the lowest root length (12.51 cm).

The interaction effect between tillage practices and organic manures was non-significant for root length.

3.6 Root Volume

Root volume followed a trend similar to that of root length. Conventional tillage (T1) produced a significantly higher root volume (58.05 cm³) than RT, MT, and ZT. The lowest root volume was recorded under zero tillage (55.48 cm³).

Among the organic inputs, phosphocompost (57.68 cm³) and FYM (57.38 cm³) were statistically at par with each other. The lowest root volume was consistently recorded under M4 (55.58 cm³). No significant interaction effect was observed between tillage and organic manures.

This may be ascribed to the enriched available nutrient content of phosphocompost, particularly N, P, and K. Enrichment of compost with rock phosphate and microbial inoculants significantly enhances phosphorus availability, which is often a limiting factor in heavy clay soils. Similar results were reported by Magdum (2022).

3.7 Effect of Tillage and Organic Inputs on Yield of Cotton

Table 13. Effect of tillage and organic inputs on seed cotton yield and stalk yield

Treatments	Seed cotton yield (q ha^{-1})	Stalk yield (q ha^{-1})
Factor A (Tillage practices)		
T_1 – CT	14.10	27.78
T_2 – RT	10.22	19.70
T_3 – MT	9.47	18.04
T_4 – ZT	4.87	9.13
SE (m)±	**0.456**	**0.143**
CD @ 5%	**1.317**	**0.414**
Factor B (Organic manures)		
M_1 - FYM @ 10 t ha^{-1}	9.22	17.90
M_2 - VC @ 5 t ha^{-1}	10.55	20.66
M_3 - PC @ 5 t ha^{-1}	11.25	22.07
M_4 – NM	7.63	14.02
SE (m) ±	**0.456**	**0.143**
CD @ 5%	**1.317**	**0.414**
Interaction of tillage practices and organic manures (A × B)		
SE (m) ±	**0.912**	**0.287**
CD @ 5%	**2.634**	**0.827**

3.7.1 Seed Cotton Yield

Seed cotton yield was significantly influenced by the different tillage treatments, as presented in Table 13. Conventional tillage (T1) emerged as the most productive system, recording the significantly highest yield of 14.10 q ha-1. Conversely, zero tillage (T4) resulted in the lowest yield, at 4.87 q ha-1. T1 (CT) was followed by reduced tillage (T2; 10.22 q ha-1) and minimum tillage (T3; 9.47 q ha-1), which produced intermediate yields, with T2 slightly outperforming T3. Although these practices moderately improved resource-use efficiency, they were statistically inferior to conventional tillage.

The consistent superiority of conventional tillage can be attributed to improved soil tilth, aeration, and root proliferation, which collectively enhance nutrient uptake and water availability, thereby supporting better boll development and filling. Intensive tillage practices can contribute to enhanced cotton productivity by improving root-soil interactions and ensuring uniform stand establishment. The significant yield reduction under zero tillage may be associated with poor seedbed preparation, restricted soil microbial activity, and reduced nutrient mineralisation, which cumulatively limit crop growth and boll formation. Similar findings were reported by Saleem *et al.* (2022).

A significant positive effect of organic manure application on seed cotton yield was observed. Phosphocompost (M3) was the most effective treatment, producing 11.25 q ha-1. This was followed by vermicompost (M2) and FYM (M1), which also significantly enhanced yields over the control. Vermicompost-treated plots yielded 10.55 q ha-1, while the application of FYM resulted in 9.22 q ha-1. The lowest seed cotton yield was observed under no-manure application (M4), at 7.63 q ha-1.

Table 14. Interaction effect of tillage and organic inputs on seed cotton yield

	Seed cotton yield (q ha^{-1})				
Treatments	**T_1 (CT)**	**T_2 (RT)**	**T_3 (MT)**	**T_4 (ZT)**	**Mean B**
M_1 - FYM @ 10 t ha^{-1}	13.61	10.11	8.55	4.61	9.22
M_2 - VC @ 5 t ha^{-1}	16.22	10.61	10.05	5.51	10.55
M_3 - PC @ 5 t ha^{-1}	16.77	11.66	11.05	5.33	11.25
M_4 - No manure	9.77	8.50	8.22	4.05	7.63
Mean A	14.10	10.22	9.47	4.87	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.456	0.456	0.912		
CD @ 5 %	1.317	1.317	2.634		

3.7.2 Stalk Yield

Tillage treatments exerted a significant influence on stalk yield, as shown in Table 13. The significantly highest stalk yield was recorded under conventional tillage (T1), at 27.78 q ha-1. This was followed by reduced tillage (T2), which resulted in an intermediate stalk yield of 19.70 q ha-1, and minimum tillage (T3), at 18.04 q ha-1. In contrast, zero tillage (T4) resulted in the lowest stalk yield, at 9.13 q ha-1.

The superior performance under this treatment can be attributed to better soil tilth, enhanced moisture retention, and favourable conditions for root proliferation. These improvements in the root-zone environment likely supported greater vegetative biomass accumulation. The reduced performance under zero tillage could be due to restricted root growth and poor aeration, which limited nutrient and water uptake and thereby affected vegetative growth. Similar results were reported by Saleem *et al.* (2022).

Among organic manure treatments, phosphocompost (M3) significantly outperformed the other treatments in promoting stalk biomass, recording 22.07 q ha-1. Vermicompost (M2) followed, yielding 20.66 q ha-1. Farmyard manure (M1) showed moderate performance, with a yield of 17.90 q ha-1. In contrast, the control treatment without organic inputs (M4) produced the lowest stalk yield, at 14.02 q ha-1.

This may be linked to balanced nutrient release, especially phosphorus, which is critical for cell division and elongation and thus facilitates robust plant growth. Similar results were reported by Singh *et al.* (2020).

The interaction effect between tillage and organic inputs was statistically significant. The combination of conventional tillage with phosphocompost (T1M3) resulted in the highest stalk yield, likely due to the combined effect of improved soil physical conditions and a steady nutrient supply.

Table 15. Interaction effect of tillage and organic inputs on stalk yield

	Stalk yield (q ha^{-1})				
Treatments	**T_1 (CT)**	**T_2 (RT)**	**T_3 (MT)**	**T_4 (ZT)**	**Mean B**
M_1 - FYM @ 10 t ha^{-1}	26.95	19.62	16.34	8.72	17.91
M_2 - VC @ 5 t ha^{-1}	32.61	20.69	19.31	10.03	20.66
M_3 - PC @ 5 t ha^{-1}	33.39	22.87	21.56	10.47	22.07
M_4 - No manure	18.19	15.64	14.96	7.30	14.02
Mean A	27.78	19.70	18.04	9.13	
	Factor A	Factor B	Int. A x B		
SE (m) ±	0.143	0.143	0.287		
CD @ 5 %	0.414	0.414	0.827		

4. Conclusion

The study demonstrated that tillage practices and organic manure application significantly influenced cotton growth, root characteristics, and yield under the Vertisol conditions evaluated. Conventional tillage generally resulted in greater plant height, reproductive growth, root development, seed cotton yield, and stalk yield than reduced, minimum, and zero tillage. Farmyard manure at 10 t ha^{-1} produced the greatest plant height, whereas phosphocompost at 5 t ha^{-1} showed favourable effects on branching, square and boll formation, root growth, and yield. Conventional tillage produced a seed cotton yield of 14.10 q ha^{-1} and a stalk yield of 27.78 q ha^{-1}. Among the organic manure treatments, phosphocompost produced the highest mean seed cotton yield of 11.25 q ha^{-1} and a mean stalk yield of 22.07 q ha^{-1}. Significant interactions between tillage and organic manure were observed for several growth and yield traits, indicating that crop response depended on the combined management practices. Within the conditions of this experiment, appropriate tillage and organic manure management were important determinants of cotton productivity in Vertisols.

5. Limitations

This study was conducted at a single research farm during *Kharif* 2023 using 16 treatment combinations with three replications, while growth observations were based on five randomly selected plants from each treatment plot. Consequently, seasonal and location-specific variability could not be evaluated. The measurements were limited to the reported biometric, root, and yield parameters under the specific Vertisol conditions and manure application rates tested. Future studies should include multiple seasons, locations, and greater replication to confirm the consistency of the observed treatment responses.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/166682