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Effect of crop residue mulching on soil fertility under rainfed Bt-cotton

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ABSTRACT

A field experiment was conducted during the kharif season of 2025-26 at the Research Farm of the Cotton Research Unit, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra, to study the effect of different crop residue mulches on the physical and chemical properties of soil under rainfed Bt-cotton. A randomized block design (RBD) with four replications was adopted, wherein the treatments included the application of different crop residue mulches in combination with the general recommended dose of fertilizer (GRDF). Treatments comprised: GRDF, GRDF + Mulching with wheat straw @ 50% of potential yield, GRDF + Mulching with cotton stalk @ 50% of potential yield, GRDF + Mulching with soybean straw @ 75% of potential yield and GRDF + Mulching with weed biomass. Numerically the lowest bulk density (1.40 Mg m^{-3}), highest hydraulic conductivity (0.77 cm hr^{-1}) and highest mean weight diameter (0.76 mm) were observed in GRDF + Mulching with soybean straw @ 75% of potential yield. Soil moisture content was significantly highest in GRDF + Mulching with soybean straw @ 75% of potential yield at both the grand growth stage (20.99%) and at harvest (15.01%), which was statistically at par with GRDF + Mulching with weed biomass. Numerically the lowest pH (8.05) was observed in GRDF + Mulching with weed biomass, and numerically the lowest EC (0.38 dS m^{-1}) was observed in GRDF, GRDF + Mulching with soybean straw @ 75% of potential yield and GRDF + Mulching with weed biomass. Significantly maximum organic carbon (4.84 g kg^{-1}) was recorded in GRDF + Mulching with weed biomass, which was statistically at par with GRDF + Mulching with soybean straw @ 75% of potential yield (4.81 g kg^{-1}) and GRDF + Mulching with wheat straw @ 50% of potential yield (4.78 g kg^{-1}). Significantly highest available nitrogen ($186.26 \text{ kg ha}^{-1}$) and phosphorus (18.92 kg ha^{-1}) were found in GRDF + Mulching with soybean straw @ 75% of potential yield, which was statistically at par with GRDF + Mulching with weed biomass and GRDF + Mulching with wheat straw @ 50% of potential yield. The highest potassium content ($378.20 \text{ kg ha}^{-1}$) was also recorded in GRDF + Mulching with soybean straw @ 75% of potential yield, statistically at par with GRDF + Mulching with weed biomass. Numerically highest available zinc, iron, manganese and copper were all observed in GRDF + Mulching with soybean straw @ 75% of potential yield.

Keywords: Crop residue mulching, Soybean and wheat straw, Cotton stalk, Weed biomass, Soil fertility, Bt-cotton

Introduction

Cotton (*Gossypium hirsutum* L.) occupies a central place in the Indian agricultural economy, and, alongside its importance to the textile industry, is popularly referred to as the country's "white gold" (Directorate of Cotton Development, 2017) [1]. A large share of the crop is grown under rainfed conditions, which leaves productivity closely tied to seasonal rainfall and to the underlying condition of the soil. In the Vidarbha region of Maharashtra, where cotton is grown almost entirely under rainfed Inceptisols, continuous cultivation and the common practice of removing or burning crop residues after harvest have gradually eroded soil organic matter and fertility. Burning a tonne of residue destroys not only its organic carbon but also the nitrogen, phosphorus, potassium and sulphur it contains, representing a substantial and avoidable nutrient loss (Bhattacharjya *et al.*, 2019) [2].

Returning these residues to the soil surface as mulch offers a low-cost alternative that keeps this nutrient pool in circulation. As residues decompose, they add organic matter, encourage microbial activity and gradually release nutrients back into the soil, while the surface cover itself moderates temperature, conserves moisture and improves aggregation and porosity (Turmel *et al.*, 2015; Fu *et al.*, 2021) [4, 3]. Comparable improvements in soil physical and chemical condition have been reported for rainfed Bt-cotton grown on deep black Vertisols under residue-based nutrient management (Sanjivkumar *et al.*, 2022) [5], and a closely related trial carried out at the same research farm found that soybean straw mulching improved soil fertility under rainfed cotton more than fertiliser use alone (More *et al.*, 2025) [6].

Since the type and quantity of residue used are likely to influence the extent of these changes, and this had not been closely examined for wheat straw, cotton stalk, soybean straw and weed biomass side by side on the Inceptisols of Akola, the present investigation was undertaken to assess the effect of crop residue mulching on the physical and chemical properties of soil under rainfed *Bt*-cotton.

Materials and methods

A field experiment on “Effect of crop residue mulch on soil physical and chemical properties under rainfed *Bt*-cotton” was conducted during the kharif season of 2025-26 at the Research Farm of the Cotton Research Unit, Dr. Panjabrao Deshmukh Krishi Vidyapeeth (PDKV), Akola, Maharashtra, India, representing the third year of trial established in 2023-24. The site was fairly uniform and levelled in topography, situated at 20°42'01" N latitude and 77°04'05" E longitude, at an elevation of about 297 m above mean sea level, in a semi-arid tract that receives most of its rainfall from the south-west monsoon between June and October. The soil under study was classified as an Inceptisol, having a bulk density of 1.48 Mg m⁻³ and a hydraulic conductivity of 0.65 cm hr⁻¹. It was slightly alkaline in reaction (pH 8.08), non-saline (EC 0.32 dS m⁻¹), medium calcareous and contained a medium level of soil organic carbon (4.48 g kg⁻¹). The nutrient status indicated low available nitrogen (165.33 kg ha⁻¹), very low available phosphorus (12.14 kg ha⁻¹) and high available potassium (343.68 kg ha⁻¹). Among micronutrients, the soil was deficient in available zinc but sufficient in available iron, manganese and copper. The experiment was laid out in a Randomized Block Design (RBD) comprising five treatments with four replications, using *Bt*-cotton hybrid Ajeet 199 BG-II sown by dibbling on 2 July 2025 at a spacing of 90 × 45 cm. The treatments included: GRDF (T₁), GRDF + Mulching with wheat straw @ 50% of potential yield (T₂), GRDF + Mulching with cotton stalk @ 50% of potential yield (T₃), GRDF + Mulching with soybean straw @ 75% of potential yield (T₄) and GRDF + Mulching with weed biomass (T₅). The general recommended fertilizer dose (GRDF) consisted of 90 kg N ha⁻¹, 45 kg P₂O₅ ha⁻¹ and 45 kg K₂O ha⁻¹ along with FYM @ 5 t ha⁻¹, supplied through urea, single superphosphate (SSP) and muriate of potash (MOP), respectively; the entire dose of phosphorus and potassium, together with 25% of the nitrogen dose, was applied basally at sowing, with the remaining nitrogen top-dressed in two equal splits at square formation and flowering. Crop residue mulches were applied to the soil surface on the same date as sowing. Composite soil samples were collected treatment-wise from the 0-20 cm layer after harvest using a stainless-steel auger, air-dried, gently crushed with a wooden pestle to break down clods, and passed through a 2 mm sieve (a 0.5 mm sieve for organic carbon). The processed samples were analysed for bulk density, hydraulic conductivity, mean weight diameter, soil moisture, pH, electrical conductivity, organic carbon, available nitrogen, phosphorus, potassium and available micronutrients (Zn, Fe, Mn, Cu) using standard procedures: bulk density by the clod-coating method (Blake *et al.*, 1986) [7], hydraulic conductivity by the constant-head method (Klute *et al.*, 1986) [8], mean weight diameter using Yoder's wet-sieving apparatus and soil moisture gravimetrically (Black, 1965) [9], soil pH and electrical conductivity in a 1:2.5 soil-water suspension (Jackson, 1973) [10], organic carbon by the Walkley *et al.* (1934) [11] wet-oxidation method, available nitrogen by the alkaline potassium permanganate method (Subbiah *et al.*, 1956) [12], available phosphorus by Olsen's method (Olsen *et al.*, 1954) [13], available potassium by neutral normal ammonium acetate extraction and flame photometry (Jackson, 1973) [10], and DTPA-extractable zinc, iron, manganese and copper by atomic absorption spectrophotometry (Lindsay *et al.*, 1978) [14]. The data on physical and chemical properties were compiled in tabular form and statistically analysed following the procedure for a Randomized Block Design described by Gomez *et al.* (1984) [15].

Results and discussion

Physical properties of soil

Bulk density

Soil bulk density recorded after harvest of *Bt*-cotton varied only slightly across treatments (Table 1), with the lowest value (1.40 Mg m⁻³) under GRDF + Mulching with weed biomass, closely followed by GRDF + Mulching with soybean straw @ 75% of potential yield (1.41 Mg m⁻³) and GRDF + Mulching with wheat straw @ 50% of potential yield (1.42 Mg m⁻³), while GRDF recorded the highest value (1.43 Mg m⁻³).

This modest decline under mulching is best explained by the steady addition and breakdown of organic material at the soil surface, which builds up organic matter and encourages the formation of more stable aggregates; the associated microbial and fungal activity, together with root exudates, opens up soil structure and raises porosity, which in turn lowers bulk density. The comparatively larger drop under weed biomass and soybean straw likely reflects how quickly these particular residues break down: being succulent and low in lignin, they release organic matter into the soil more readily within a single season than the more fibrous wheat straw or cotton stalk.

A similar pattern of improved aggregation following straw incorporation and residue mulching has been reported by Kharche *et al.* (2013) [16], Zhang *et al.* (2016) [17] and Chatterjee *et al.* (2017) [18], while Singh *et al.* (2024) [19] more recently observed a comparable fall in surface bulk density under paddy straw mulching, attributing it to the same gradual accumulation of organic matter from decomposing residues.

Hydraulic conductivity and mean weight diameter

Hydraulic conductivity and mean weight diameter (MWD) likewise showed only numerical differences among treatments (Table 1). Hydraulic conductivity ranged from 0.71 to 0.77 cm hr⁻¹, highest under GRDF + Mulching with soybean straw @ 75% of potential yield, followed by GRDF + Mulching with weed biomass (0.76 cm hr⁻¹) and GRDF + Mulching with wheat straw @ 50% of potential yield (0.75 cm hr⁻¹). The lowest values were recorded under GRDF + Mulching with soybean straw @ 75% of potential yield (0.73 cm hr⁻¹) and GRDF (0.71 cm hr⁻¹). Mean weight diameter followed much the same order, ranging from 0.67 mm under GRDF to 0.76 mm under GRDF + Mulching with soybean straw @ 75% of potential yield, with GRDF + Mulching with weed biomass (0.73 mm) and GRDF + Mulching with wheat straw @ 50% of potential yield (0.71 mm) intermediate.

Bulk density and mean weight diameter are, in effect, two faces of the same structural change as root channels, fungal hyphae, microbial polysaccharides and other binding agents produced during residue decomposition draw soil particles into larger, more stable aggregates, the accompanying rise in macroporosity and pore connectivity is what allows hydraulic conductivity to increase alongside them. The stronger response under soybean straw is consistent with its higher application rate and faster decomposition, which sustains an active carbon source for soil microorganisms for longer during the season, whereas the slower, more fibrous decomposition of wheat straw and cotton stalk limits their effect within a single cropping cycle weed biomass, being similarly soft tissue, produced a comparable benefit. These results agree with Singh *et al.* (2024) [19], who linked zero tillage and residue mulching to improved infiltration and reduced compaction, and with Chatterjee *et al.* (2017) [18], who recorded roughly a 6.7% rise in mean weight diameter after a single season of residue mulching. Zhang *et al.* (2016) [17] similarly found that straw incorporation raised mean weight diameter and identified a positive relationship between aggregate stability, organic carbon and nutrient status.

Soil moisture content

Soil moisture content, measured at the grand growth stage and again at harvest, was significantly influenced by mulching (Table 2, Fig 1). At the grand growth stage, moisture content was highest under GRDF + Mulching with soybean straw @ 75% of potential yield (20.99%), statistically at par with GRDF + Mulching with weed biomass (20.59%), GRDF + Mulching with wheat straw @ 50% of potential yield (20.04%) and GRDF + Mulching with cotton stalk @ 50% of potential yield (19.61%), and significantly higher than GRDF (18.42%). The same ranking held at harvest, when moisture content under GRDF + Mulching with soybean straw @ 75% of potential

yield (15.01%) was again at par with GRDF + Mulching with weed biomass (13.80%) and GRDF + Mulching with cotton stalk @ 50% of potential yield (12.68%), while GRDF retained only 8.99%.

The better moisture retention under soybean straw and weed biomass mulching can be attributed to the greater surface cover these residues provide, which intercepts solar radiation and reduces wind movement at the soil surface, combined with the structural benefits already noted above — lower bulk density and higher hydraulic conductivity and aggregate stability allow rainfall to infiltrate and be stored rather than running off. The comparatively low moisture recorded under T_1 reflects its greater exposure to direct evaporation and to weed competition for the limited moisture available under rainfed conditions.

Table 1. Effect of crop residue mulching on soil physical properties after harvest of *Bt*-cotton

Tr. No.	Treatment details	BD (Mg m ⁻³)	HC (cm hr ⁻¹)	MWD (mm)
T ₁	GRDF	1.43	0.71	0.67
T ₂	GRDF + Mulching with wheat straw @ 50% of potential yield	1.42	0.75	0.71
T ₃	GRDF + Mulching with cotton stalk @ 50% of potential yield	1.43	0.73	0.69
T ₄	GRDF + Mulching with soybean straw @ 75% of potential yield	1.41	0.77	0.76
T ₅	GRDF + Mulching with weed biomass	1.40	0.76	0.73
SE(m)±		0.036	0.074	0.047
CD at 5%		NS	NS	NS
Initial		1.48	0.65	0.62

This finding is consistent with Chatterjee *et al.* (2017) [18] and Singh *et al.* (2024) [19], both of whom linked the improved aggregation seen

under residue mulching to higher soil moisture content.

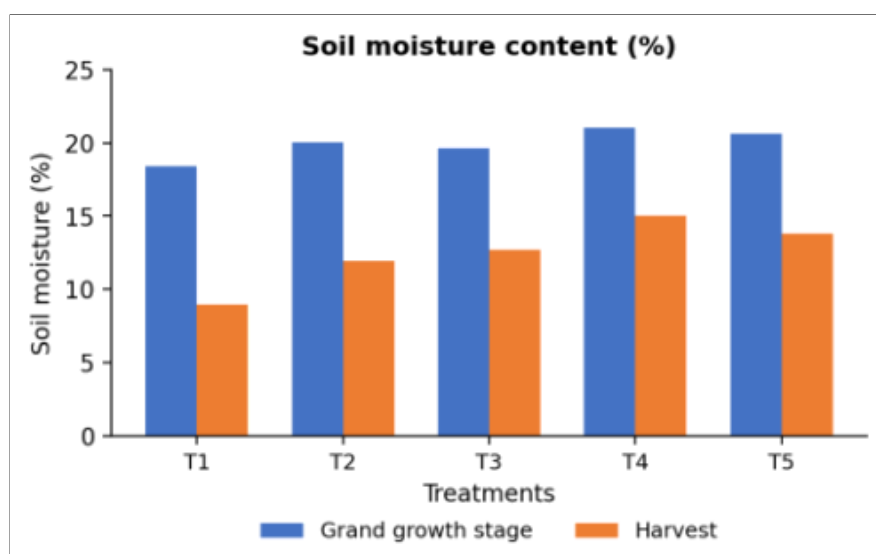


Figure 1. Soil moisture content as influenced by different residue mulching treatments

Chemical properties of soil

Soil pH and electrical conductivity

Soil pH and electrical conductivity (EC) after harvest varied only marginally among treatments, with no statistically significant differences (Table 3). Soil pH ranged narrowly from 8.05 to 8.10; numerically the lowest pH (8.05) was observed in GRDF + Mulching with weed biomass, with GRDF and GRDF + Mulching with soybean straw @ 75% of potential yield both at 8.06, and the highest values under GRDF + Mulching with wheat straw @ 50% of potential yield (8.10) and GRDF + Mulching with cotton stalk @ 50% of potential yield. Electrical conductivity varied between 0.38 and 0.42 dS m⁻¹; numerically the lowest EC (0.38 dS m⁻¹) was observed in GRDF, GRDF + Mulching with soybean straw @ 75% of potential yield and

GRDF + Mulching with weed biomass, and the highest under GRDF + Mulching with cotton stalk @ 50% of potential yield (0.42 dS m⁻¹). The slightly lower pH under the more rapidly decomposing residues — weed biomass and soybean straw — is consistent with the release of CO₂ and organic acids during microbial breakdown; soybean straw, being a legume residue, is also prone to nitrogen mineralisation and nitrification, both of which release H⁺ ions into the soil. Wheat straw and cotton stalk, being higher in lignin, decompose more slowly and therefore have less influence on pH within a single season, leaving GRDF closest to the original soil reaction. The modest rise in EC across treatments most likely reflects the fertiliser and FYM applied uniformly through GRDF, with the somewhat higher EC under cotton stalk mulching possibly linked to the gradual release of soluble potassium, calcium and magnesium from this residue.

Table 2. Effect of crop residue mulching on soil moisture content at grand growth stage and after harvest of *Bt*-cotton

Tr. No.	Treatment details	Soil moisture (%) at grand growth stage	Soil moisture (%) at harvest
T ₁	GRDF	18.42	8.99
T ₂	GRDF + Mulching with wheat straw @ 50% of potential yield	20.04	11.92
T ₃	GRDF + Mulching with cotton stalk @ 50% of potential yield	19.61	12.68
T ₄	GRDF + Mulching with soybean straw @ 75% of potential yield	20.99	15.01
T ₅	GRDF + Mulching with weed biomass	20.59	13.80
SE(m)±		0.77	1.17
CD at 5%		1.68	2.56

These observations are in line with Bama *et al.* (2017) [20], who reported a decline in soil pH under residue mulching combined with or-

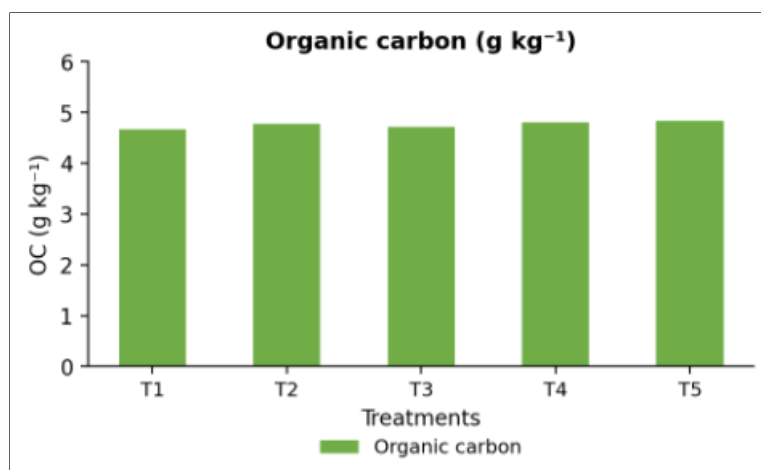
ganic and inorganic nutrient sources, alongside EC changes that depended on residue type and cropping system.

Organic carbon

Organic carbon content differed significantly among treatments (Table 3, Fig 2). Significantly maximum organic carbon (4.84 g kg⁻¹) was recorded in GRDF + Mulching with weed biomass, which was statistically at par with GRDF + Mulching with soybean straw @ 75% of potential yield (4.81 g kg⁻¹) and GRDF + Mulching with wheat straw @ 50% of potential yield (4.78 g kg⁻¹), while GRDF recorded the lowest value (4.66 g kg⁻¹).

The larger gains under weed biomass and soybean straw mulching reflect how readily these soft, low-lignin residues decompose and add organic matter to the soil within a single cropping season, whereas the moderate decomposition rate of wheat straw produced an intermediate rise and the more fibrous, lignified cotton stalk contributed comparatively little to the organic carbon pool over the same period. The small increase recorded under GRDF alone is likely attributable to the FYM applied as part of the recommended dose rather than to any residue effect.

This pattern agrees with Chen *et al.* (2023) [21] and with Morey *et al.* (2025) [6], whose companion trial at the same research farm similarly found that soybean straw mulching under GRDF improved soil fertility, followed by weed biomass mulching, in rainfed cotton.

**Figure 2.** Soil organic carbon as influenced by different residue mulching treatments

Available nitrogen, phosphorus and potassium

Available nitrogen, phosphorus and potassium in the soil after harvest all differed significantly with mulching treatment (Table 4, Figs 3-5). Significantly highest available nitrogen and phosphorus (186.26 and 18.92 kg ha⁻¹, respectively) were found in GRDF + Mulching with soybean straw @ 75% of potential yield, which was statistically at par with GRDF + Mulching with weed biomass (184.14 and 18.26 kg ha⁻¹) and GRDF + Mulching with wheat straw @ 50% of potential

yield (183.72 and 17.88 kg ha⁻¹), while GRDF recorded the lowest values for both nutrients (178.38 and 16.08 kg ha⁻¹). Available potassium followed the same trend, the highest content (378.20 kg ha⁻¹) was recorded in GRDF + Mulching with soybean straw @ 75% of potential yield, which was statistically at par with GRDF + Mulching with weed biomass (375.33 kg ha⁻¹) and GRDF + Mulching with wheat straw @ 50% of potential yield (372.18 kg ha⁻¹), and lowest under GRDF (368.54 kg ha⁻¹).

Table 3. Effect of crop residue mulching on soil chemical properties after harvest of *Bt*-cotton

Tr. No.	Treatment details	pH (1:2.5)	EC (dS m ⁻¹)	OC (g kg ⁻¹)
T ₁	GRDF	8.06	0.38	4.66
T ₂	GRDF + Mulching with wheat straw @ 50% of potential yield	8.10	0.40	4.78
T ₃	GRDF + Mulching with cotton stalk @ 50% of potential yield	8.10	0.42	4.72
T ₄	GRDF + Mulching with soybean straw @ 75% of potential yield	8.06	0.38	4.81
T ₅	GRDF + Mulching with weed biomass	8.05	0.38	4.84
SE(m)±		0.022	0.019	0.029
CD at 5%		NS	NS	0.064
Initial		8.08	0.36	4.48

(continued on next page)

Although all three nutrients rose under mulching, the underlying reasons differed somewhat. Nitrogen release depended strongly on residue quality: soybean straw, with its comparatively narrow carbon-to-nitrogen ratio, and the soft tissue of weed biomass both mineralise rapidly, whereas the wider C:N ratio of wheat straw slows release, and the fibrous, lignified cotton stalk may even cause short-term microbial immobilisation of soil nitrogen, which likely explains its relatively modest showing among the mulched treatments. Phosphorus availability in this mildly alkaline soil is chiefly limited by fixation with calcium, a constraint that organic acids released during the decomposition of soybean straw and weed biomass appear to ease, while the higher microbial activity they support probably also raises phosphatase activity and converts more organically bound phosphorus into forms the plant can use; wheat straw released phosphorus at a

moderate rate, and the slow, fibrous decomposition of cotton stalk kept its phosphorus release closest to that of GRDF alone. Potassium, held largely in soluble ionic form within plant cells rather than in structural tissue, is released quickly once residues come into contact with soil moisture regardless of lignin content, which explains the narrower spread among treatments; the higher residue quantity applied through the 75% soybean straw treatment nonetheless gave it the largest total potassium contribution.

These findings agree with Jayaraman *et al.* (2021) [22] and Mali *et al.* (2020) [23], who both recorded increases in available nitrogen, phosphorus and potassium following the incorporation or retention of organic residues, and with Morey *et al.* (2025) [6], whose parallel trial at the same research farm found a comparable improvement in soil fertility under GRDF combined with soybean straw mulching.

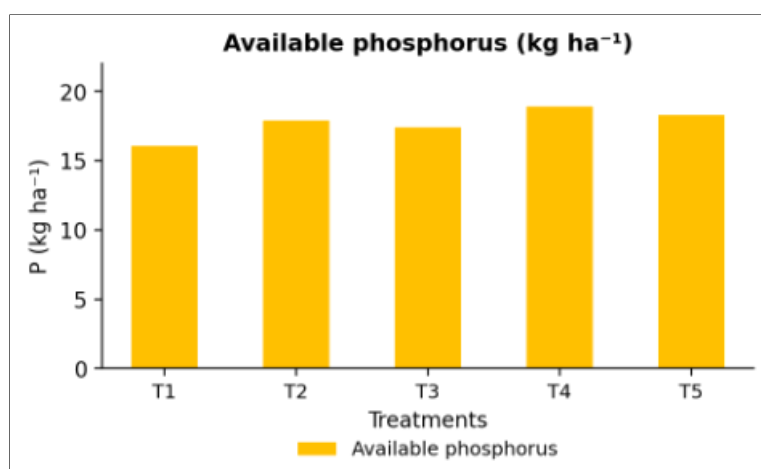
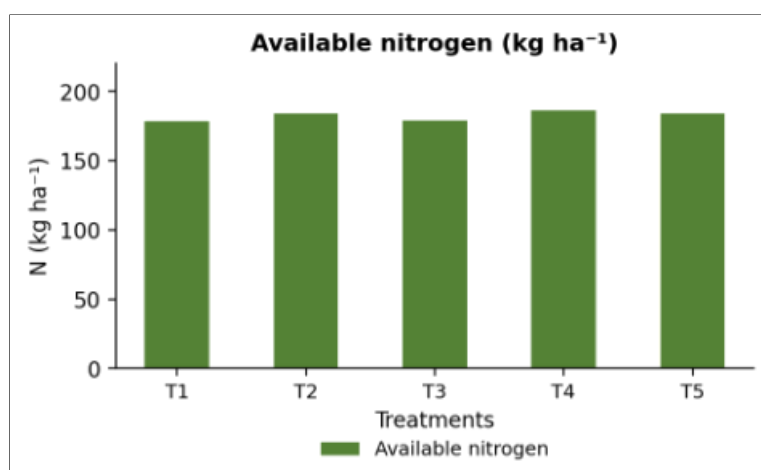


Figure 3. Soil available nitrogen as influenced by different residue mulching treatments

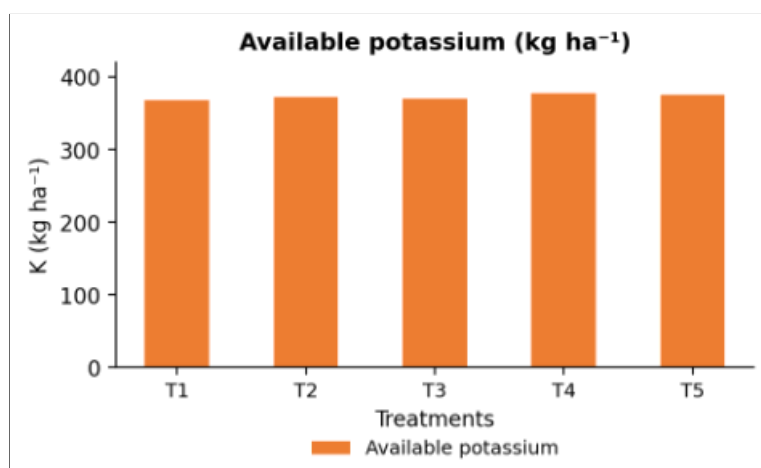


Figure 4. Soil available phosphorus as influenced by different residue mulching treatments

Available zinc and iron

The available zinc and iron content of the soil (Table 5) was influenced only numerically by mulching, with no significant differences among treatments. Available zinc ranged from 0.61 to 0.72 mg kg⁻¹, highest under GRDF + Mulching with soybean straw @ 75% of potential yield, followed by GRDF + Mulching with weed biomass (0.69 mg kg⁻¹), GRDF + Mulching with cotton stalk @ 50% of potential yield (0.67 mg kg⁻¹) and GRDF + Mulching with wheat straw @ 50% of potential yield (0.65 mg kg⁻¹), with GRDF recording the lowest value (0.61 mg kg⁻¹). Available iron showed a similar pattern, ranging from 6.37 mg kg⁻¹ under GRDF + Mulching with cotton stalk @ 50% of potential yield and GRDF to 6.47 mg kg⁻¹ under GRDF + Mulching with soybean straw @ 75% of potential yield.

In this alkaline Inceptisol, zinc and iron behave similarly because their availability is governed by comparable chemical constraints: in

the absence of organic inputs, zinc tends to precipitate as insoluble hydroxides and carbonates and iron as insoluble oxides and hydroxides, both of which are favoured by the prevailing pH. Decomposing residues counter this by releasing organic acids and chelating agents that form soluble metal-organic complexes with zinc and iron keeping both elements in a form, plants can take up. Because this benefit hinges on decomposition, the more rapidly breaking-down soybean straw and weed biomass produced the largest gains, while wheat straw and cotton stalk contributed comparatively little within a single growing season.

These results align with Jayaraman *et al.* (2021) [22], who reported higher DTPA-extractable zinc and iron under residue retention in a Vertisol and attributed the effect to organic acids increasing solubility, and with Mali *et al.* (2020) [23], who likewise observed improved zinc availability under integrated resource conservation practices.

Table 4. Effect of crop residue mulching on available nutrient status of soil after harvest of *Bt*-cotton

Tr. No.	Treatment details	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
T ₁	GRDF	178.38	16.08	368.54
T ₂	GRDF + Mulching with wheat straw @ 50% of potential yield	183.72	17.88	372.18
T ₃	GRDF + Mulching with cotton stalk @ 50% of potential yield	179.20	17.40	370.66
T ₄	GRDF + Mulching with soybean straw @ 75% of potential yield	186.26	18.92	378.20
T ₅	GRDF + Mulching with weed biomass	184.14	18.26	375.33
SE(m)±		1.62	0.44	2.25
CD at 5%		4.98	1.35	6.93
Initial		165.33	12.14	343.68

Table 5. Effect of crop residue mulching on available micronutrient status of soil after harvest of *Bt*-cotton

Tr. No.	Treatment details	Zn (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Cu (mg kg ⁻¹)
T ₁	GRDF	0.61	6.37	7.58	2.26
T ₂	GRDF + Mulching with wheat straw @ 50% of potential yield	0.65	6.39	7.67	2.30
T ₃	GRDF + Mulching with cotton stalk @ 50% of potential yield	0.67	6.37	7.62	2.29
T ₄	GRDF + Mulching with soybean straw @ 75% of potential yield	0.72	6.47	7.67	2.34
T ₅	GRDF + Mulching with weed biomass	0.69	6.44	7.61	2.32
SE(m)±		0.048	0.085	0.078	0.046
CD at 5%		NS	NS	NS	NS
Initial		0.54	6.27	7.30	1.68

Available manganese and copper

Available manganese and copper (Table 5) also increased numerically under mulching, without significant differences among treatments. Available manganese ranged from 7.58 to 7.67 mg kg⁻¹, with the highest values under GRDF + Mulching with wheat straw @ 50% of potential yield and GRDF + Mulching with soybean straw @ 75% of potential yield, followed by GRDF + Mulching with cotton stalk @ 50% of potential yield (7.62 mg kg⁻¹) and GRDF + Mulching with weed biomass (7.61 mg kg⁻¹); GRDF recorded the lowest value (7.58 mg kg⁻¹). Available copper ranged from 2.26 mg kg⁻¹ under GRDF to 2.34 mg kg⁻¹ under GRDF + Mulching with soybean straw @ 75% of potential yield, with GRDF + Mulching with weed biomass (2.32 mg kg⁻¹) and GRDF + Mulching with cotton stalk @ 50% of potential yield (2.29 mg kg⁻¹) close behind.

As with zinc and iron, the organic acids and localised reducing conditions generated during residue breakdown help keep manganese and

copper in soluble, plant-available forms rather than allowing them to oxidise into less accessible states. Manganese behaved slightly differently from the other three micronutrients, however: wheat straw mulching matched soybean straw in its effect despite decomposing more slowly, suggesting that manganese release in this soil depends less on decomposition speed than zinc, iron or phosphorus do. Copper, by contrast, tracked the faster-decomposing residues more closely, and the narrow spread among the mulched treatments suggests its release owes more to the general rise in microbial activity common to all mulched plots than to the decomposition rate of any one residue.

These results agree with Jayaraman *et al.* (2021) [22] and Mali *et al.* (2014) [24], both of whom reported improved manganese availability under residue-based and integrated nutrient management, and with Mali *et al.* (2020) [23], who similarly recorded an improvement in copper status under integrated organic and inorganic management at the same station.

Conclusion

From the above experimental results, it can be concluded that application of the general recommended dose of fertilizers (90:45:45 N:P₂O₅:K₂O kg ha⁻¹ + FYM @ 5 t ha⁻¹) along with soybean straw mulching @ 75% of potential yield found beneficial for improving the physical and chemical properties of soil under rainfed Bt-cotton, while weed biomass mulching was also found beneficial for improving soil physical and chemical health. Bulk density, hydraulic conductivity, mean weight diameter, soil pH, electrical conductivity and the available micronutrients zinc, iron, manganese and copper changed only numerically across treatments, whereas soil moisture content, organic carbon and the available macronutrients nitrogen, phosphorus and potassium increased significantly under mulching.

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