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Changes in carbon dynamics with crop residue mulching under Bt-cotton

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Abstract
During 2024-25, a field study was undertaken at the Cotton Research Unit of Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra, to study the changes in carbon dynamics with crop residue mulching under Bt-cotton. The experiment was laid out in a Randomized Block Design (RBD) with four replications and five treatments. The treatments involved the application of different crop residue mulches along with the general recommended dose of fertilizers (GRDF). Treatments comprised: T_1 (GRDF), T_2 (GRDF + Mulching with wheat straw @ 50% of potential yield), T_3 (GRDF + Mulching with cotton straw @ 50% of potential yield), T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield) and T_5 (GRDF + Mulching with weed biomass).
The treatment receiving GRDF + Mulching with soybean straw @ 75% of potential yield (T_4) recorded significantly higher carbon fractions compared to other treatments. It registered the maximum very labile carbon and labile carbon, indicating a notable improvement in the active carbon pool, along with the highest total organic carbon. Significantly highest less labile carbon was also observed in GRDF + Mulching with soybean straw @ 75% of potential yield (T_4), which was statistically at par with GRDF + Mulching with weed biomass (T_5). For non-labile carbon, the highest value was recorded in GRDF + Mulching with cotton stalk @ 50% of potential yield (T_3), whereas the lowest was observed under GRDF (T_1) alone. In terms of water-soluble carbon, GRDF + Mulching with soybean straw @ 75% of potential yield (T_4) recorded the highest value, which was statistically at par with GRDF + Mulching with weed biomass (T_5) and GRDF + Mulching with wheat straw @ 50% of potential yield (T_2), indicating considerable variation among treatments. Similarly, the highest potential mineralizable carbon was obtained in GRDF + Mulching with soybean straw @ 75% of potential yield (T_4), which was statistically at par with GRDF + Mulching with weed biomass (T_5) and GRDF + Mulching with wheat straw @ 50% of potential yield (T_2).

Keywords: Crop residue mulching, carbon dynamics, carbon pools and Bt-cotton

Introduction
Cotton, derived from the Arabic term *qutn*, is a soft and fibrous staple material produced in the boll or protective capsule surrounding the seeds of *Gossypium* species within the Malvaceae family. Chemically, cotton fibre is composed almost entirely of cellulose, accompanied by minor proportions of waxes, lipids, pectins, and water. Cotton is a major fibre and cash crop in India, playing a key role in the country's agricultural and industrial economy. India ranks first in cultivation area and second in production globally. In India, *G. hirsutum* represents more than 95% of the total cotton area and production. Currently, genetically-modified cotton (Bt-cotton) accounts for more than 95% of the total cultivated area. About 67% of India's cotton is grown in rain-fed areas, while the remaining 33% is cultivated on irrigated lands (Ministry of Textiles, 2023) [31]. During 2024-25, Bangladesh emerged as the largest importer of raw cotton, bringing in 8.20 million bales, followed by Vietnam (7.40 million bales), China (6.80 million bales) and Pakistan (5.50 million bales). Notably, China's imports fell sharply by 55%, from 14.97 million bales the previous year to 6.80 million bales, whereas India's imports surged by 194%, rising from 0.89 to 2.60 million bales. On the export side, Brazil, the United States and Australia together accounted for about 69% of global raw cotton exports, with Brazil leading at 13.00 million bales a 95% increase over 2022-23. India ranked fourth, exporting 1.4 million bales. In

terms of consumption, China remained the largest consumer (32.18% of global usage), followed by India (21.88%), Pakistan (8.84%), Bangladesh (7.12%), Vietnam (6.35%) and Turkey (6.01%).

According to the Third Advance Estimates for 2024-25, India's cotton production is projected at 306.92 lakh bales, lower than the 325.22 lakh bales recorded in 2023-24. Among the states, Maharashtra tops the list with an output of 92.32 lakh bales, followed by Gujarat (69.61 lakh bales), Telangana (55.50 lakh bales), Karnataka (22.67 lakh bales) and Rajasthan (17.86 lakh bales) (Anonymous, 2025) [4].

Annually, India produces around 500-550 million tonnes (Mt) of crop residue from both on-farm and off-farm sources. Crop residue mulching plays a vital role in regulating carbon dynamics by serving as a key source of organic carbon input to the soil. Residues left on the soil surface act as a major source of organic matter, which upon decomposition increases very labile, labile and stable carbon pools, thereby enriching soil fertility. Mulching also promotes microbial activity, leading to greater carbon mineralization and humus formation, while simultaneously reducing carbon losses through erosion and volatilization. By improving soil aggregation and moisture retention, it helps in the stabilization of carbon and enhances potential carbon sequestration. Overall, crop residue mulching contributes to maintaining a positive carbon balance, improves soil health and supports the sustainability of agroecosystems. Archna *et al.* (2009) highlighted that modifying residue management practices along with the addition of organic manures can enhance carbon sequestration by improving soil organic carbon (SOC) levels. Increasing carbon inputs and maintaining soil organic carbon (SOC) can be achieved through practices such as applying organic fertilizers, incorporating cover crops into crop rotations and leaving crop residues on or within the soil (Lehtinen *et al.*, 2014) [26].

Materials and Methods

The field experiment on "Effect of crop residue mulch on soil fertility, yield and nutrient uptake by Bt-cotton under rainfed condition'' was initiated during 2023-24 at Research Farm, Cotton Research Unit, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola (Maharashtra). The present investigation was carried out during 2024-25 (Second year) entitled "Effect of crop residue mulching on carbon dynamics under Bt-cotton in Inceptisols". The site was fairly uniform and levelled in topography. The soil under study was classified as Inceptisols, 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 (electrical conductivity: 0.32 dSm^{-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}), high available potassium (343.68 kg ha^{-1}) and available sulphur was medium (10.52 mg kg^{-1}). Among micronutrients, the soil was deficient in DTPA-extractable zinc (Zn) but sufficient in DTPA-extractable iron (Fe), manganese (Mn) and copper (Cu).

The experiment was conducted in a Randomized Block Design (RBD) comprising five treatments with four replications. The treatments included: T_1 (GRDF), T_2 (GRDF + Mulching with wheat straw @ 50% of potential yield), T_3 (GRDF + Mulching with cotton straw @ 50% of potential yield), T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield) and T_5 (GRDF + Mulching with weed biomass). The cotton hybrid Ajeet 199 BG-II was sown at a spacing of 90 × 45 cm. The general recommended fertilizer dose (GRDF) consisted of 90 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1} and 45 kg K_2O ha^{-1} along with FYM @ 5 t ha^{-1}, supplied through Urea, Single Superphosphate (SSP) and Muriate of Potash (MOP), respectively.

Prior to sowing, surface soil samples (0-20 cm) were collected treatment-wise from the experimental field and a similar set of samples was taken again after the harvest of the crop. The collected soils were air-dried, gently crushed with a wooden pestle to break down clods, and then sieved through appropriate mesh sizes. These processed samples were subsequently analyzed for various soil parameters using standard analytical procedures. At crop maturity, representative plant samples were collected, processed and subjected to analysis for soil carbon pools (very labile, labile, less labile and non-labile), total organic carbon, water soluble carbon and potential mineralizable carbon using the standard procedures outlined by Walkley and Black (1934) [44], Chan *et al*. (2001) [13], Tiessen and Moir (1993) [42], Mc Gill *et al.* (1986) and Anderson (1982) [2]. The data related to different carbon pools, including total organic carbon, water-soluble carbon and potential mineralizable carbon, were compiled in tabular form and subjected to statistical analysis using the methods outlined by Gomez and Gomez (1984) [18].

Results and Discussion

Soil carbon pools

Very labile

As indicated in table 1, various mulching treatments combined with the GRDF (General Recommended Dose of Fertilizers) significantly influenced the very labile carbon pool of the soil. The treatment T_1 (GRDF alone), recorded the lowest very labile carbon value (2.15 g kg^{-1}), indicating that mulching significantly enhances the labile carbon content compared to fertilizer application alone. Among the mulched treatments, T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield) produced the highest value of very labile carbon (2.60 g kg^{-1}). The combined use of GRDF and soybean straw creates optimal conditions for rapid decomposition and mineralization, significantly enhancing very labile carbon an easily available energy source for soil microbes and an important indicator of improved soil quality. According to Dolan *et al.* (2006) [15], the continuous return of crop residues to the soil, especially under conditions of minimal soil disturbance, is strongly associated with increased SOC concentrations. This is because residue retention contributes not only to the stable forms of carbon but also to the more dynamic fractions, including the very labile carbon (VLC).

These results are consistent with the findings of Bhattacharyya *et al.* (2009) [11], who reported that short-term residue management and legume-based crop rotations enhanced carbon inputs, improving active carbon fractions in surface soil. Similarly, Sanjuna *et al.* (2021) also noted that organic amendments increased very labile carbon (VLC) in the soil. The findings are in line with the results reported by Alam *et al.* (2020) [1] and Ansari *et al.* (2022) [5]. The results are in conformity with Ekta *et al.* (2025), who reported the highest very labile carbon, likely due to increased organic matter input. The very labile carbon (CVL), being the most easily decomposable fraction, is closely associated with the addition of organic residues in the soil.

Labile

As indicated in table 1, various mulching treatments combined with the GRDF (General Recommended Dose of Fertilizers) significantly influenced the labile carbon pool of the soil. Among the treatments, the treatment (T_1), which received only GRDF without any mulching, recorded the lowest labile carbon content (1.60 g kg^{-1}). The highest value was observed in T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield), which recorded (1.80 g kg^{-1}) significantly higher than the T_1 (GRDF) and all other treatments. This indicates that soybean straw, owing to its higher organic matter and nutrient content, plays a significant role in enhancing soil labile carbon. The combined application of GRDF and soybean straw creates a favourable environment for microbial activity, faster residue decomposition, and greater accumulation of labile carbon, which is vital for soil fertility and nutrient cycling.

These results are consistent with the findings of Prasad *et al.* (2016) [36], who observed that organic matter application significantly improved labile carbon pools over 100% inorganic fertilizers. Similarly, Bhattacharyya *et al.* (2018) [10] reported that crop residue application in cotton fields increased labile carbon, supporting microbial activity and stable carbon, aiding in long-term carbon storage. The findings are in line with the results reported by Venkatesh *et al.* (2013) [43], Das *et al.* (2016), Phalke *et al.* (2017) [35] and Jadhao *et al.* (2018) [22]. The results are in conformity with Hema *et al.* (2019) [20] who reported higher labile carbon levels with manure application compared to inorganic fertilizers alone.

Less labile

According to table 1, the integration of mulching treatments with the GRDF (General Recommended Dose of Fertilizers) resulted in a significant variation in less labile carbon pool content of the soil. The treatment, T_1 (GRDF alone), recorded the lowest value (1.95 g kg^{-1}), highlighting that the application of fertilizer without organic residue input contributes less to the accumulation of less labile carbon. In contrast, all mulched treatments demonstrated higher values, with the maximum observed in T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield) (2.30 g kg^{-1}), which was statistically at par with T_5 (GRDF + Mulching with weed biomass) (2.22 g kg^{-1}). The application of the general recommended dose of fertilizers along with soybean straw and weed biomass increases less labile carbon because these residues contain more resistant carbon compounds such as cellulose, hemicellulose, and lignin.

While GRDF provides nutrients that stimulate microbial activity, the decomposition of these complex residues occurs more slowly than that of easily degradable materials. As microbes utilize the readily available fractions first, the remaining portion of soybean straw and weed biomass contributes to the less labile carbon pool, which is moderately stable and decomposes over a longer period. The highest soil less labile carbon content was observed with soybean straw application, reflecting the long-term benefits of incorporating organic residues. Shelke *et al.* (2019) [40] reported that long-term application of FYM and green leaf manure significantly increased the less labile carbon pool. Similar findings were also observed by Nath *et al.* (2015) [33], Das *et al.* (2016) and Swati *et al.* (2018). Similar results were also reported by Babu *et al.* (2020) [7] who found that the application of organic amendments enhanced the less labile carbon pool, especially in the deeper soil layers.

Non labile

As shown in table 1, non-labile carbon pool of the soil was significantly influenced by the application of various mulching treatments along with the GRDF (General Recommended Dose of Fertilizers). The treatment (T_1: GRDF only) recorded the lowest non-labile carbon (4.33 g kg^{-1}), whereas mulched treatments showed higher values, with the maximum observed in T_3 (GRDF + Mulching with cotton stalk @ 50% of potential yield) (4.80 g kg^{-1}). The application of the general recommended dose of fertilizers (GRDF) along with cotton stalks increases non-labile carbon because cotton stalks are rich in lignin, cellulose, and other recalcitrant structural compounds that resist microbial decomposition. While GRDF stimulates microbial activity by supplying essential nutrients, the slow breakdown of cotton stalks results in the accumulation of stable organic matter in the soil.

Surface soils generally show higher non-labile carbon levels compared to subsurface layers, likely due to their finer texture and greater clay content, which restrict the downward movement of organic carbon compounds and aid in their stabilization. Bhattacharya *et al.* (2007) reported that the use of FYM combined with crop residue incorporation led to a reduction in non-labile carbon pools. These results are in line with Das *et al.* (2016), who found that materials with a wider C:N ratio (e.g., CR-cereal residue) enhanced recalcitrant carbon fractions. The findings are in line with the results reported by Ghosh *et al.* (2012) [17], Alam *et al.* (2020) [1].

Total Organic Carbon

The table 1 indicated statistically significant variations in the Total Organic Carbon (TOC) content of soil under different treatments involving the General Recommended Dose of Fertilizers (GRDF), with and without mulching. The treatment, T_1 (GRDF alone), recorded the lowest TOC value of 10.04 g kg^{-1}, indicating limited organic carbon buildup when fertilizer is applied without organic residue inputs. In contrast, T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield) recorded the highest TOC value of (11.19 g kg^{-1}). Application of the general recommended dose of fertilizers (GRDF) along with soybean straw significantly increases total organic carbon (TOC) because the combination provides both essential nutrients and organic matter that improve soil carbon inputs and stimulate microbial processes.

Returning crop residues to the soil and incorporating them has become a widely accepted practice for maintaining total organic carbon (TOC) stocks in agricultural lands (Hadas *et al*., 2004; Lian *et al*., 2016) [19, 27]. These results are consistent with those reported by Kirkby *et al.* (2013) [24], who found that the addition of straw together with nitrogen fertilizer led to a greater increase in total organic carbon compared to the addition of straw alone. Incorporation of rice straw, in particular, has been shown to enhance the TOC pool by 13% and increase its labile carbon fractions by 42% compared to the use of chemical fertilizers alone (Liu *et al*., 2014) [28]. The findings are in line with the results reported by Benbi *et al.* (2015) [8], Phalke *et al.* (2017) [35] and Ansari *et al.* (2022) [5].

Table 1: Soil carbon pools as influenced by different treatments

T.N.	Treatment Details	Soil Carbon Pools (g kg^{-1})				
		Very labile	Labile	Less labile	Non labile	TOC
T_1	GRDF	2.15	1.60	1.95	4.33	10.04
T_2	GRDF + Mulching with wheat straw @ 50% of potential yield	2.34	1.68	2.16	4.68	10.86
T_3	GRDF + Mulching with cotton stalk @ 50% of potential yield	2.22	1.65	2.08	4.80	10.74
T_4	GRDF + Mulching with soybean straw @ 75% of potential yield	2.60	1.80	2.30	4.48	11.19
T_5	GRDF + Mulching with weed biomass	2.43	1.72	2.22	4.44	10.79
	SE (m) ±	0.03	0.02	0.03	0.02	0.06
	CD at 5%	0.10	0.05	0.10	0.05	0.17

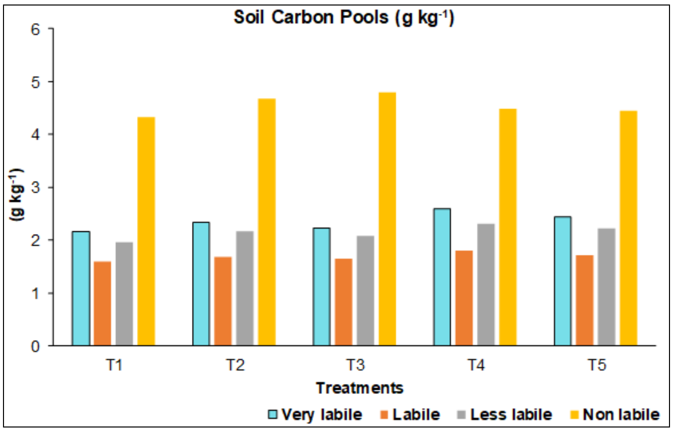

Fig 1: Soil carbon pools as influenced by different treatments

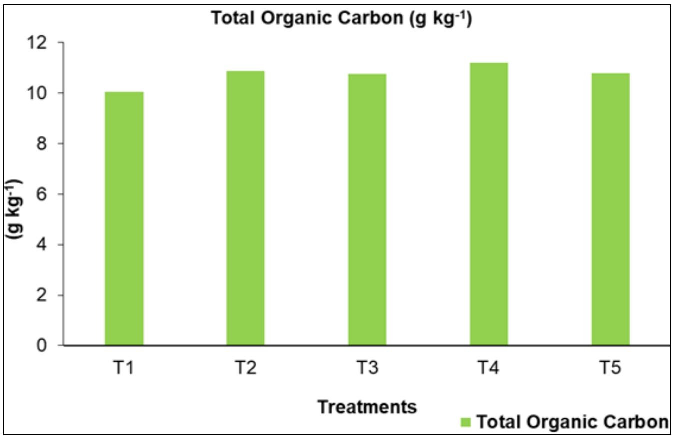

Fig 2: Soil Total Organic Carbon as influenced by different treatments

Water Soluble Carbon

The table 2 indicated significant influence of different mulching treatments in combination with the GRDF (General Recommended Dose of Fertilizer) on water soluble carbon (WSC) in soil. Among the treatments, T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield) recorded the highest WSC value of (215 mg kg^{-1}), which was statistically at par with T_5 (GRDF + Mulching with weed biomass mulch) (207 mg kg^{-1}) and T_2 (GRDF + Mulching with wheat straw @ 50% of potential yield) recorded (198 mg kg^{-1}) of WSC. The treatment T_1 (GRDF only) recorded the lowest WSC (185 mg kg^{-1}). The application of GRDF along with soybean straw, weed biomass, and wheat straw enhances water-soluble carbon (WSC) in the soil because this combination supplies both essential nutrients and a diverse range of organic residues that release soluble compounds during decomposition. Under nutrient-rich conditions, these residues decompose more efficiently, releasing soluble organic molecules into the soil solution and enriching the WSC pool.

These results align with the findings of Yagi *et al.* (2005) [45], who suggested that the priming effect from added fertilizers or organic inputs can enhance microbial activity, leading to greater decomposition of organic matter and increased WSC. Similarly, Brar *et al.* (2013) [12] reported that balanced fertilization combined with organic amendments significantly increased soil WSC compared to the control, up to a depth of 60 cm. The findings are in line with the results reported by Phalke *et al.* (2017) [35] and Kumar *et al.* (2018) [25]. Similar results were reported by Ann *et al.* (2023) observed that residue retention enhanced WSC by 20-90% across various bed systems, with elevated beds showing up to 11% more WSC than flat beds.

Potential Mineralizable Carbon

The table 2 indicated the effect of various significant mulching treatments combined with GRDF (General Recommended Dose of Fertilizers) on potential mineralizable carbon (PMC) in soil. The data clearly demonstrates that all mulching treatments (T_2 to T_5) increased PMC levels compared to the (T_1), which only included GRDF without mulching (34.52 mg 100 g^{-1} soil). Treatment T_4 (GRDF + Mulching with soybean straw @ 75% of potential yield) recorded the highest PMC value (45.16 mg 100 g^{-1} soil), which was statistically at par with T_5 (GRDF + Mulching with weed biomass) (43.62 mg 100 g^{-1} soil) and T_2 (GRDF + Mulching with wheat straw @ 50% of potential yield) (40.33 mg 100 g^{-1} soil). GRDF supplies nitrogen and other nutrients that improve microbial efficiency in decomposing organic matter, while soybean straw and weed biomass contribute easily degradable compounds, and wheat straw adds more complex carbon fractions. Thus, the integration of GRDF with multiple crop residues creates a synergistic effect that boosts microbial activity, accelerates residue breakdown, and increases mineralizable carbon, thereby improving soil fertility.

These results align with the findings of Pal *et al.* (2019) [34], who reported that the combined use of organic and inorganic nutrient sources significantly enhanced potential mineralizable carbon in soil. Similar findings were also reported by Khalil *et al.* (2005) [23], Mishra *et al.* (2008) [32], Hossain *et al.* (2017) [21] and Pushpa *et al.* (2017). The findings are in conformity with those of Rakesh *et al.* (2021) [38], who observed that incorporation of crop residues into the soil significantly increased carbon footprints due to higher carbon mineralization, while surface retention of residues reduced carbon footprints and contributed to environmental sustainability.

Table 2: Water Soluble Carbon and Potential Mineralizable Carbon of soil as influenced by different treatments

Tr. No.	Treatment Details	Water Soluble Carbon (mg kg^{-1})	Potential Mineralizable Carbon (mg 100 g^{-1} soil)
T_1	GRDF	185	34.52
T_2	GRDF + Mulching with wheat straw @ 50% of potential yield	198	40.33
T_3	GRDF + Mulching with cotton stalk @ 50% of potential yield	193	38.44
T_4	GRDF + Mulching with soybean straw @ 75% of potential yield	215	45.16
T_5	GRDF + Mulching with weed biomass	207	43.62
	SE (m) ±	5.41	1.72
	CD at 5%	16.67	5.30

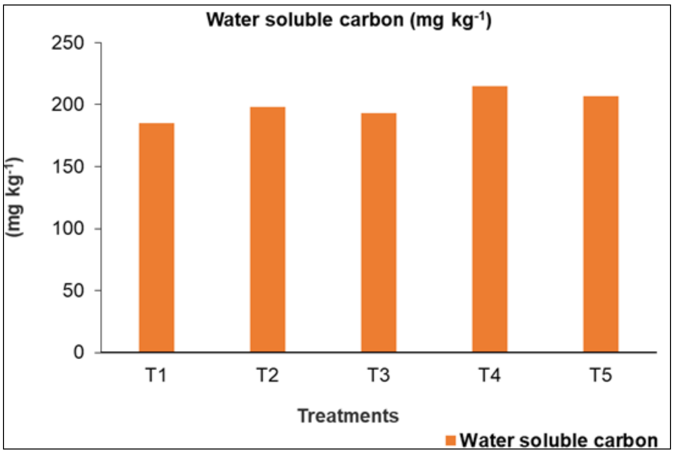

Fig 3: Water Soluble Carbon as influenced by different treatments

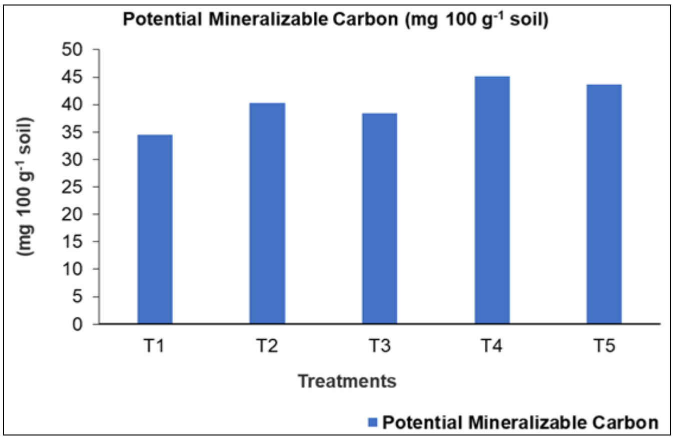

Fig 4: Potential Mineralizable Carbon as influenced by different treatments

Conclusion

It can be concluded that application of general recommended dose of fertilizers (90:45:45 N:P_2O_5:K_2O kg ha^{-1} + FYM @ 5 t ha^{-1}) along with soybean straw mulching @ 75% of potential yield found beneficial for improving soil carbon dynamics in Bt-cotton under rainfed condition, while, weed biomass also found equally beneficial in most of the parameters such as (less labile carbon pool, water soluble carbon and potential mineralizable carbon).

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