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# Effect of Mulching on Soil Health and Economics of Chickpea (*Cicer arietinum* L.) under Dryland Conditions

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***Authors' contributions***

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

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## Abstract

An experiment was conducted during the *Rabi* season of 2022–23 at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, to evaluate the effects of different mulches on soil physicochemical properties, soil microbial biomass, enzymatic activities, microbial populations, and economics of chickpea. The experiment was laid out in a randomised block design (RBD) with three replications comprising seven treatments, namely no mulch, dust mulch, paddy straw, maize stover, *Leucaena twigs*, and combinations of paddy straw or maize stover with Leucaena twigs. Among the treatments, *Leucaena twigs* @ 5 t ha$^{-1}$ recorded the highest available nitrogen (259.3 kg ha$^{-1}$), phosphorus (15.23 kg ha$^{-1}$), potassium (185 kg ha$^{-1}$), and organic carbon (0.56%). The combination of maize stover @ 2.5 t ha$^{-1}$ + *Leucaena twigs* @ 2.5 t ha$^{-1}$ recorded the highest microbial biomass carbon (178.44 µg g$^{-1}$ soil), dehydrogenase activity (18.32 µg TPF g$^{-1}$ soil 24 h$^{-1}$), alkaline phosphatase activity (115.32 µg p-NP g$^{-1}$ soil h$^{-1}$), bacterial population (16.98 CFU g$^{-1}$ soil), fungal population (14.76 CFU g$^{-1}$ soil), and actinomycetes

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population (3.48 CFU $g^{-1}$ soil). However, the combination of paddy straw @ 2.5 t $ha^{-1}$ + *Leucaena* twigs @ 2.5 t $ha^{-1}$ recorded the highest gross returns (₹100,409.80 $ha^{-1}$), net returns (₹56,281.54 $ha^{-1}$), and benefit-cost ratio (2.28). The results indicated that residue-based mulching improved soil fertility and biological activity, with maize stover + *Leucaena* twigs being particularly effective for soil biological properties, while paddy straw + *Leucaena* twigs provided the highest economic returns.

*Keywords: Chickpea; mulching; soil fertility; microbial activity; economics.*

## 1. Introduction

Mulching is an important soil and water conservation practice that helps mitigate moisture stress under dryland conditions by reducing direct soil evaporation and maintaining favourable soil moisture and temperature regimes (Ramos *et al*., 2024). Decomposition of organic mulch materials can contribute to soil organic matter and improve soil physical, chemical and biological properties, thereby promoting crop growth and productivity (Rathore *et al*., 1998; Hatfield *et al*., 2001; Bhardwaj, 2013; Deka *et al*., 2021; Gaitanis *et al*., 2023). Organic materials such as grass, sawdust, corncobs, rice husks, and wheat and rice straw can be used as locally available mulch resources (Shrivastava *et al*., 1994). Mulching has also been reported to improve crop productivity under hot and dry environmental conditions (Birbal *et al*., 2013; Rudragouda *et al*., 2025). Crop residues retained on the soil surface can contribute to soil organic carbon accumulation, improve soil structure, reduce erosion, enhance water infiltration and retention, and provide nutrients and substrates for soil biological activity (Lal, 2010). A field study involving rainfed chickpea reported improvements in soil organic carbon and available nutrients following the combined use of organic residue mulching and natural farming inputs (Tiwari *et al*., 2026). Research on soybean in a semi-arid region also showed that the mulch rate associated with the greatest soil moisture conservation was not necessarily the rate providing the most favourable economic return (Atsbeha *et al*., 2026).

Application of different mulch materials can modify soil temperature, moisture availability and other soil microclimatic conditions (Kingra & Kaur, 2017). Soil temperature is particularly important because it influences the physical, chemical and biological processes occurring in the root zone. Soil enzymes are important biocatalysts that regulate the decomposition of organic matter and transformation of nutrients and are widely recognised as sensitive indicators of soil biological functioning and soil health (Ananbeh *et al*., 2019; Wang *et al*., 2010). Soil enzyme activities are strongly influenced by soil moisture, temperature, aeration, organic matter availability and microbial activity. Under dryland conditions, fluctuations in soil moisture and temperature can adversely affect microbial processes and nutrient cycling. Mulching can modify the soil microenvironment, act as a food source and improve the conditions for microbial activity, thereby influencing soil enzyme activities and nutrient transformations (Lei *et al*., 2022; Seo *et al*., 2015). Recent evidence also indicates that straw mulching can significantly modify soil enzyme activities and thereby influence soil nutrient cycling and biological functioning (Fahad *et al*., 2024). Appropriate selection and application of mulch materials can help regulate the root-zone environment and create favourable conditions for crop establishment and subsequent growth. Therefore, assessment of soil enzyme activities provides an important biological approach for evaluating the effects of different mulching practices on soil health and nutrient cycling under dryland chickpea production. In a long-term spring maize experiment, straw mulching increased soil carbon fractions, while responses of microbial carbon-degradation genes differed between straw and plastic-film treatments (Yang *et al*., 2025).

A separate dryland maize study linked film–straw dual mulching with improved soil fertility and changes in straw-degrading bacterial communities (Yang *et al*., 2024).

Chickpea (*Cicer arietinum* L.) is one of the most important pulse crops cultivated in semi-arid and dryland regions, where it contributes substantially to dietary protein, soil fertility and farm income. However, chickpea productivity in dryland environments is frequently constrained by inadequate and uneven distribution of rainfall, high evaporative demand, unfavourable soil conditions and limited availability of soil moisture during critical stages of crop growth (Kamboj *et al*., 2025). Sustainable soil management practices that improve nutrient availability and maintain soil biological activity are therefore essential for enhancing chickpea productivity and sustaining soil health (Verma & Pradhan, 2024).

Chickpea is particularly suitable for evaluating the effects of different mulches because it is a rabi-season crop generally adapted to cool and dry conditions and is extensively cultivated under semi-arid and dryland environments. Organic materials such as rice straw and maize stubble constitute important sources of mulch in commercial crop production and can provide a practical means of improving soil quality in dryland farming systems (Kumar & Niwas, 2022). Recycling residues through surface mulching can return organic matter to the soil and support long-term soil health. However, in dryland and semi-arid regions, the availability of crop residues for mulching may be limited because residues are also required as livestock feed, particularly where livestock production forms an important component of farm livelihoods (Palsaniya *et al*., 2023). This limitation highlights the need to explore alternative and locally available biomass resources for mulching. *Leucaena leucocephala* (L.), for example, is a productive multipurpose perennial shrub or tree that can provide biomass for green manuring, fuelwood, livestock feed, pasture improvement and other purposes. Its biological nitrogen-fixation capacity and potential use in alley-cropping systems make it a potentially useful biomass resource for sustainable agricultural production (De Angelis *et al*., 2021; Palsaniya *et al*., 2023). In a faba bean-based cropping system, organic-material mulching was associated with changes in microbial communities involved in soil carbon and nitrogen cycling (Ren *et al*., 2025).

Different mulch materials, such as paddy straw, maize residues and *Leucaena* biomass, vary in their decomposition rates, nutrient-release patterns and effects on soil properties. Their individual application or combination may provide complementary benefits through improved nutrient cycling, organic matter addition and soil biological activity (Gaitanis *et al*., 2023; Hu & Zhu, 2025). However, limited information is available on the comparative effects of these mulch materials and their combinations on soil

chemical and biological properties, particularly microbial biomass, enzyme activities and microbial populations, in dryland chickpea. Furthermore, competing uses and the cost of crop residues necessitate identifying mulching practices that are both agronomically effective and economically viable. Therefore, the present study evaluated different locally available mulch materials and their combinations for improving soil health and economic returns of chickpea under dryland conditions.

## 2. Methodology

### 2.1 Experimental Site and Treatments

An experiment was conducted during the *Rabi* season of 2022–23 at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India, to evaluate the effects of different mulching treatments on soil health and economics of chickpea (*Cicer arietinum* L.) under dryland conditions. The experiment was laid out in a randomised block design (RBD) with three replications comprising seven treatments: $T_1$, no mulch; $T_2$, dust mulch; $T_3$, paddy straw @ 5 t ha$^{-1}$; $T_4$, maize stover @ 5 t ha$^{-1}$; $T_5$, *Leucaena* twigs @ 5 t ha$^{-1}$; $T_6$, paddy straw @ 2.5 t ha$^{-1}$ + *Leucaena* twigs @ 2.5 t ha$^{-1}$; and $T_7$, maize stover @ 2.5 t ha$^{-1}$ + *Leucaena* twigs @ 2.5 t ha$^{-1}$. Chickpea was sown on 12 November 2022 at a spacing of 30 cm × 10 cm using a seed rate of 80 kg ha$^{-1}$. A recommended dose of 20 kg N, 40 kg $P_2O_5$ and 20 kg $K_2O$ ha$^{-1}$ was applied uniformly to all treatments at sowing. The respective mulch materials were applied between the crop rows on 20 November 2022, 10 days after sowing.

### 2.2 Soil Sampling and Analysis

Soil samples were collected from each experimental plot at harvest to estimate available nitrogen, phosphorus, potassium and organic carbon. Available nitrogen was determined by the alkaline potassium permanganate method of Subbiah and Asija (1956), available phosphorus was determined using the Olsen method, and available potassium was determined by neutral ammonium acetate extraction followed by flame photometric determination. Soil organic carbon was estimated by the Walkley and Black method and expressed as a percentage.

### 2.3 Soil Biological Properties

Soil samples collected at 50% flowering were used to estimate soil microbial biomass carbon (SMBC), dehydrogenase activity (DHA), alkaline phosphatase activity (APA) and microbial populations. SMBC was estimated by the chloroform fumigation–extraction method and expressed as µg biomass C g$^{-1}$ soil. Dehydrogenase activity was determined following Casida *et al*. (1964) and expressed as µg TPF g$^{-1}$ soil 24 h$^{-1}$. Alkaline phosphatase activity was estimated according to Tabatabai and Bremner (1969) and expressed as µg p-nitrophenol g$^{-1}$ soil h$^{-1}$.

The populations of bacteria, fungi and actinomycetes were determined using the serial dilution and plate count technique. Nutrient agar, potato dextrose agar and actinomycetes isolation medium were used for enumeration of bacteria, fungi and actinomycetes, respectively (Gordon *et al*., 1973; Martin, 1950; Corke & Chase, 1956). The microbial populations were expressed as colony-forming units (CFU) g$^{-1}$ soil.

### 2.4 Economics

The cost of cultivation was calculated from expenditure on field preparation, seed, fertilizers, labour, mulching and other cultivation operations under each treatment. Gross returns were calculated using the prevailing market prices of chickpea seed and haulm. Net returns were calculated by deducting the cost of cultivation from gross returns. The benefit-cost ratio (B:C) was calculated as**:**

B:C ratio = Gross returns / Cost of cultivation

### 2.5 Statistical Analysis

The data on soil chemical properties, microbial biomass carbon, enzymatic activities, microbial populations and economics were subjected to analysis of variance (ANOVA) appropriate for a randomised block design. The significance of treatment effects was tested using the F-test at the 5% probability level. The standard error of the mean (SEm±) and critical difference (CD) were calculated, and treatment means were compared using Duncan's multiple range test (DMRT) at $p < 0.05$.

## 3. Results and Discussion

Table 1 shows significant differences among treatments in available N, P and K at harvest. The results indicate that $T_5$ (*Leucaena twigs* @5 t ha$^{-1}$) consistently recorded the highest available nitrogen, phosphorus, potassium and organic carbon. The increases in NPK and OC under this treatment can be attributed to the incorporation of *Leucaena* biomass with a low C:N ratio, which enhanced microbial activity and accelerated decomposition and mineralisation processes. Mulching regulated mineralization–immobilization dynamics, resulting in sustained nutrient release and improved nutrient availability throughout the crop growth period. The increase in soil organic carbon reflects the accumulation of decomposed twigs and microbial biomass. Improved phosphorus availability under *Leucaena* mulch may also be associated with the release of organic acids during decomposition, which reduced nutrient fixation and enhanced nutrient mobility in the soil. Overall, the improvement in soil chemical properties under Leucaena twig mulch indicates enhanced nutrient cycling and soil fertility. These findings corroborate earlier reports by Deka *et al*. (2021) and Gulati and Kaur (2024).

**Table 1. Effect of different mulches on soil chemical properties**

| Treatment | | Available Nitrogen Kg ha $^{-1}$ | Available Phosphorus Kg ha $^{-1}$ | Available Potassium Kg ha $^{-1}$ | O.C (%) |
|---|---|---|---|---|---|
| $T_1$ | No mulch | 218.3$^{d}$ | 12.5$^{e}$ | 130$^{e}$ | 0.45$^{e}$ |
| $T_2$ | Dust mulch | 225.$^{cd}$ | 12.89$^{e}$ | 135$^{e}$ | 0.42$^{f}$ |
| $T_3$ | Paddy Straw@5t ha$^{-1}$ | 231.7$^{bcd}$ | 13.25$^{de}$ | 146$^{d}$ | 0.47$^{d}$ |
| $T_4$ | Maize Stover@5t ha$^{-1}$ | 240.0$^{abc}$ | 13.89$^{cd}$ | 157$^{c}$ | 0.49$^{c}$ |
| $T_5$ | *Leucaena* twigs@5t ha$^{-1}$ | 259.3$^{a}$ | 15.23$^{a}$ | 185$^{a}$ | 0.56$^{a}$ |
| $T_6$ | Paddy straw @2.5t ha$^{-1}$ + *Leucaena* twigs@2.5t ha$^{-1}$ | 246.7$^{ab}$ | 14.14$^{bc}$ | 167$^{b}$ | 0.53$^{b}$ |
| $T_7$ | Maize stover @2.5t ha$^{-1}$ + *Leucaena* twigs@2.5t ha$^{-1}$ | 252.7$^{a}$ | 14.95$^{ab}$ | 174$^{b}$ | 0.55$^{a}$ |
| SEm± | | 5.833 | 0.267 | 2.30 | 0.0043 |
| C.D.(P=0.05) | | 17.97 | 0.82 | 7.10 | 0.013 |

*Note: Treatment means followed by similar letter within a column are not significantly different at p < 0.05 according to DMRT*

**Table 2. Effect of mulching on soil microbial biomass carbon and enzymatic activities at 50% flowering**

| Treatment | | Microbial Biomass carbon (µg of biomass g$^{-1}$ of soil) | Dehydrogenase enzyme (µg TPF g$^{-1}$ soil$^{-1}$ day) | Alkaline Phosphatase enzyme (µg p-NP g$^{-1}$ soil h$^{-1}$) |
|---|---|---|---|---|
| $T_1$ | No mulch | 138.44$^{ef}$ | 13.98$^{c}$ | 92.66$^{de}$ |
| $T_2$ | Dust mulch | 145.45$^{de}$ | 14.35$^{c}$ | 98.24$^{cd}$ |
| $T_3$ | Paddy Straw@5t ha$^{-1}$ | 132.66$^{f}$ | 12.79$^{d}$ | 88.36$^{e}$ |
| $T_4$ | Maize Stover@5t ha$^{-1}$ | 162.36$^{bc}$ | 15.98$^{b}$ | 108.38$^{ab}$ |
| $T_5$ | *Leucaena* twigs@5t ha$^{-1}$ | 154.97$^{cd}$ | 15.44$^{b}$ | 104.78$^{bc}$ |
| $T_6$ | Paddy straw @2.5t ha$^{-1}$ + *Leucaena* twigs@2.5t ha$^{-1}$ | 168.68$^{ab}$ | 16.28$^{b}$ | 112.45$^{a}$ |
| $T_7$ | Maize stover @2.5t ha$^{-1}$+ *Leucaena* twigs@2.5t ha$^{-1}$ | 178.44$^{a}$ | 18.32$^{a}$ | 115.32$^{a}$ |
| SEm± | | 3.39 | 0.30 | 2.26 |
| C.D.(P=0.05) | | 10.46 | 0.94 | 6.97 |

*Note: Treatment means followed by similar letter within a column are not significantly different at p < 0.05 according to DMRT*

Soil microbial biomass carbon (SMBC) and soil enzymatic activities, namely dehydrogenase (DHA) and alkaline phosphatase (APA), were significantly influenced by different mulching treatments. Treatment $T_7$ (maize stover @ 2.5 t ha$^{-1}$ + *Leucaena* twigs @ 2.5 t ha$^{-1}$) recorded the highest SMBC (178.44 µg biomass g$^{-1}$ soil), DHA (18.32 µg TPF g$^{-1}$ soil day$^{-1}$), and APA (115.32 µg p-NP g$^{-1}$ soil h$^{-1}$) and remained statistically at par with $T_6$ (paddy straw @ 2.5 t ha$^{-1}$ + *Leucaena twigs* @ 2.5 t ha$^{-1}$). In contrast, treatment $T_3$, involving application of paddy straw @5 t ha$^{-1}$, recorded significantly lower SMBC (132.66 µg biomass g$^{-1}$ soil), DHA (12.79 µg TPF g$^{-1}$ soil day$^{-1}$), and APA (88.36 µg p-NP g$^{-1}$ soil h$^{-1}$), representing reductions of 25.65%, 30.18%, and 23.37%, respectively, compared to $T_7$.

The enhanced SMBC, dehydrogenase, and alkaline phosphatase activities under combined residue treatments were attributed to the relatively narrow C:N ratios of maize stover and Leucaena twigs, which promoted faster decomposition, timely nutrient release, and greater availability of labile carbon substrates for microbial growth. Residue quality and retention modified the soil microclimate by improving moisture retention and moderating soil temperature, thereby creating favourable hydrothermal conditions for microbial proliferation, enzyme synthesis, and nutrient cycling processes, including carbon and nitrogen transformation. These processes contributed to soil organic carbon accumulation and stabilization of microbial biomass within soil organic matter pools, resulting in improved soil biological functioning and more active microbial populations. These observations are consistent with the findings of Duanyuan *et al*. (2023), Bongiorno *et al*. (2019), Choudhary *et al*. (2019) and Dey *et al*. (2025), who reported that residue quality, organic carbon availability, and soil microclimatic conditions strongly influence soil microbial biomass and enzymatic activities.

Table 3 indicates that soil microbial populations were significantly influenced by different mulching treatments. Treatment $T_7$ (maize stover @ 2.5 t ha$^{-1}$ + *Leucaena* twigs @ 2.5 t ha$^{-1}$) recorded the highest bacterial (16.98 cfu g$^{-1}$ soil), fungal (14.76 cfu g$^{-1}$ soil), and actinomycete (3.48 cfu g$^{-1}$ soil) populations and was statistically at par with $T_6$ (paddy straw @ 2.5 t ha$^{-1}$ + *Leucaena* twigs @ 2.5 t ha$^{-1}$). In contrast, the sole application of paddy straw @ 5 t ha$^{-1}$ ($T_3$) recorded significantly lower bacterial (11.85 cfu g$^{-1}$ soil), fungal (10.35 cfu g$^{-1}$ soil), and actinomycetes (2.08 cfu g$^{-1}$ soil) populations, showing reductions of approximately 31%, 42%, and 40%, respectively, compared to $T_7$.

This may be explained by the regulation of soil temperature, conservation of moisture (Zhang *et al*., 2020) and a continuous supply of substrates for microbial growth under loose, well-aerated soil conditions. Similar findings were reported by Deka *et al*. (2021). Conversely, the lower bacterial, fungal, and actinomycetes populations under sole paddy straw application ($T_3$) were likely due to its high C:N ratio and recalcitrant nature, which caused temporary nitrogen immobilization during early decomposition, limiting

nutrient availability and microbial proliferation. Similar effects of high-carbon residues on soil microbial populations have been reported by Yu *et al*. (2020).

**Table 3. Effect of different mulches on microbial population (cfu $g^{-1}$) at 50% flowering**

| Treatment | | Bacterial population (cfu $g^{-1}$ soil) | Fungal population (cfu $g^{-1}$ soil) | Actinomycetes population (cfu $g^{-1}$ soil) |
|---|---|---|---|---|
| $T_1$ | No mulch | $12.68^{d}$ | $11.120^{de}$ | $2.320^{e}$ |
| $T_2$ | Dust mulch | $14.21^{c}$ | $11.780^{cd}$ | $2.440^{e}$ |
| $T_3$ | Paddy Straw@5t $ha^{-1}$ | $11.85^{e}$ | $10.350^{e}$ | $2.080^{f}$ |
| $T_4$ | Maize Stover@5t $ha^{-1}$ | $15.42^{b}$ | $13.440^{b}$ | $2.980^{c}$ |
| $T_5$ | *Leucaena* twigs@5t $ha^{-1}$ | $14.83^{bc}$ | $12.380^{c}$ | $2.740^{d}$ |
| $T_6$ | Paddy straw @2.5t $ha^{-1}$ + *Leucaena* twigs@2.5t $ha^{-1}$ | $16.47^{a}$ | $14.120^{ab}$ | $3.180^{b}$ |
| $T_7$ | Maize stover @2.5t $ha^{-1}$+ *Leucaena* twigs@2.5t $ha^{-1}$ | $16.98^{a}$ | $14.760^{a}$ | $3.480^{a}$ |
| SEm± | | 0.266 | 0.272 | 0.040 |
| C.D.(P=0.05) | | 0.82 | 0.84 | 0.12 |

*Note: Treatment means followed by similar letter within a column are not significantly different at p < 0.05 according to DMRT*

**Table 4. Effect of different mulches on economics of chickpea**

| Treatment | | Cost of cultivation (Rs. $ha^{-1}$) | Gross returns (Rs. $ha^{-1}$) | Net returns (Rs. $ha^{-1}$) | B:C ratio |
|---|---|---|---|---|---|
| $T_1$ | No mulch | 33428.28 | 55896.1 | 22467.82 | 1.67 |
| $T_2$ | Dust mulch | 37428.28 | 62607.84 | 25179.56 | 1.67 |
| $T_3$ | Paddy Straw@5t $ha^{-1}$ | 41628.28 | 89280.5 | 47652.22 | 2.14 |
| $T_4$ | Maize Stover@5t $ha^{-1}$ | 41628.28 | 68484 | 26855.72 | 1.65 |
| $T_5$ | *Leucaena* twigs@5t $ha^{-1}$ | 46628.28 | 80304.56 | 33676.28 | 1.72 |
| $T_6$ | Paddy straw @2.5t $ha^{-1}$ + *Leucaena* twigs@2.5t $ha^{-1}$ | 44128.28 | 100409.8 | 56281.54 | 2.28 |
| $T_7$ | Maize stover @2.5t $ha^{-1}$+ *Leucaena* twigs@2.5t $ha^{-1}$ | 44128.28 | 74954.56 | 30826.28 | 1.70 |

*Note: Treatment means followed by similar letter within a column are not significantly different at p < 0.05 according to DMRT*

Table 4 shows variation in the cost of cultivation, gross returns, net returns and benefit–cost (B:C) ratio among mulching treatments. The highest cost of cultivation was recorded with *Leucaena* twigs @5t $ha^{-1}$(46628.28 Rs. $ha^{-1}$). The lowest cost of cultivation (33428.28 Rs. $ha^{-1}$) was observed under no mulch treatment. The highest B:C ratio was observed in $T_6$ (paddy straw @2.5t ha-1 + *Leucaena* twigs@2.5t $ha^{-1}$) whereas lower values were recorded under no mulch and dust mulch treatments. Among the treatments, T6 (Paddy straw @2.5 t $ha^{-1}$ + *Leucaena* twigs @2.5 t $ha^{-1}$) recorded the highest gross returns (100409.8₹ $ha^{-1}$), net returns (56281.54₹ $ha^{-1}$) and B:C ratio (2.28). This economic performance was attributed to improved productivity, nutrient availability and soil moisture, consistent with findings reported by Deka *et al*. (2021).

## 4. Conclusion

The study revealed that different mulching treatments significantly influenced the soil chemical and biological properties of chickpea under dryland conditions. Among the treatments, application of *Leucaena* twigs @ 5 t $ha^{-1}$ recorded the highest available nitrogen (259.3 kg $ha^{-1}$), phosphorus (15.23 kg $ha^{-1}$), potassium (185 kg $ha^{-1}$) and organic carbon (0.56%). However, the combination of maize stover @ 2.5 t $ha^{-1}$ + *Leucaena* twigs @ 2.5 t $ha^{-1}$ was most effective in enhancing soil biological activity, recording the highest microbial biomass carbon, dehydrogenase and alkaline phosphatase activities, and bacterial, fungal and actinomycetes populations. In terms of economic performance, the combination of paddy straw @ 2.5 t $ha^{-1}$ + *Leucaena* twigs @ 2.5 t $ha^{-1}$ recorded the highest gross returns (₹100,409.80 $ha^{-1}$), net returns (₹56,281.54 $ha^{-1}$) and benefit-cost ratio (2.28). These findings suggest that combining locally available crop residues with Leucaena biomass may be a promising mulching option for improving soil properties and farm profitability in dryland chickpea production. Further evaluation across seasons and locations is required to establish the consistency of these responses.

## 5. Limitations

The study was conducted at one location during a single rabi season, so the consistency of the treatment responses across years and locations remains uncertain. Soil chemical properties were assessed at harvest, whereas microbial biomass, enzyme activities and microbial populations were measured at 50% flowering. Consequently, the results characterise these specific sampling stages rather than changes throughout the growing season. The economic findings reflect the costs and returns reported for the study period. Further assessment across seasons and locations would help establish the reproducibility 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. ChatGPT, Claude and Perplexity 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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