



RESEARCH ARTICLE

Impact of small millet-legume preceding cropping system on toria performance, oil productivity and soil fertility in the NEH Region of India

Balram Yadav¹, Vishram Ram¹, Amit Kumar², A K Singh¹, Sanjay Swami¹, Lala I P Ray¹, Rizwanul Helim¹, Kenny Zohminglana¹, Durgesh Kumar Maurya³, Maram Bhargav Reddy^{1*}, Anjali Taku¹ & Piyush Kumar^{4*}

¹Department of Agronomy, School of Natural Resources Management, College of Post Graduate Studies in Agricultural Sciences (CPGS-AS), Central Agricultural University (Imphal), Umiam 793 301, Meghalaya, India

²Department of Agronomy, Dr. Rammanohar Lohiya Avadh University, Ayodhya 224 001, Uttar Pradesh, India

³Department of Agronomy, Krishi Vigyan Kendra, Sant Kabir Nagar 272 175, Uttar Pradesh, India

⁴Division of Plant Pathology, Faculty of Agriculture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Wadura 193 201, Jammu and Kashmir, India

*Correspondence email - marambhargavreddy@gmail.com, rdpiyush001@gmail.com

Received: 24 December 2025; Accepted: 30 June 2026; Available online: Version 1.0: 21 September 2026

Cite this article: Balram Y, Vishram R, Amit K, Singh AK, Sanjay S, Lala IPR, Rizwanul H, Kenny Z, Durgesh KM, Maram BR, Anjali T, Piyush K. Impact of small millet-legume preceding cropping system on toria performance, oil productivity and soil fertility in the NEH Region of India. Plant Science Today. 2026; 13(sp5): 1-12. <https://doi.org/10.14719/pst.13345>

Abstract

A two-year field study (2023–24 to 2024–25) was undertaken at the College of Post Graduate Studies (CPGS) farm Kyrdemkulai, Meghalaya, India, to evaluate the residual impact of millet–legume-based cropping systems on growth, productivity and oil quality of toria (*Brassica rapa* var. *toria*) including soil fertility. The experiment was laid out in a randomised block design (RBD) with 12 millet–legume intercropping combinations under additive (1 : 1 and 1 : 2) and replacement (1 : 1) series, along with four monocultures of finger millet, foxtail millet, soybean and green gram as controls. Growth traits (plant height, branching), yield parameters and soil properties were significantly influenced by the preceding systems. Sole legumes, particularly soybean and green gram, along with millet–legume additive combinations, recorded superior performance, with toria seed yield ranging from 649.6–854.8 kg ha⁻¹ and mean oil content of 33.0–34.6 %, resulting in oil yield of 222.6–290.8 kg ha⁻¹. Soil analysis showed notable improvements under legume-inclusive treatments, with available nitrogen (266.5–306.2 kg ha⁻¹), phosphorus (25.6–37.0 kg ha⁻¹), potassium (207.0–265.2 kg ha⁻¹), organic carbon (1.02–1.26 %) and enzyme activities (urease: 24.97–27.97 µg NH₄⁻ g⁻¹ soil hr⁻¹; protease: 14.06–16.18 µg tyrosine g⁻¹ soil hr⁻¹; dehydrogenase: 105.5–131.2 µg TPF g⁻¹ soil 24 hr⁻¹) surpassing sole millet and control plots. The findings demonstrate that millet–legume sequences, especially those including sole legumes and additive intercropping, enhance toria productivity, oil yield and soil health, providing a sustainable cropping strategy for marginal rainfed systems in the NEH Region.

Keywords: agroecosystem sustainability; carbon dynamics, intercropping; microbial activity, oilseed quality, resource-use efficiency

Introduction

Millets and legumes represent the backbone of sustainable cropping systems in the North-East Hill (NEH) Region of India because of their adaptability to marginal lands, sloping terrains and low-input production conditions. Millets are naturally climate-resilient cereals with low external input requirements and continue to hold a central position in traditional NEH farming systems, supporting smallholder livelihoods under pronounced resource and climatic constraints (1, 2). Legumes complement millet-based systems by providing protein-rich food and enhancing soil fertility through biological nitrogen (N) fixation and the return of organic residues, which together strengthen soil chemical and biological properties. Their integration as intercrops or in crop rotations has consistently improved soil organic carbon concentrations, available N pools and microbial and enzymatic activity, leading to sustained improvements in soil health. These cumulative benefits frequently

translate into higher crop productivity, enhanced nutrient-use efficiency in succeeding crops and improved long-term sustainability of the production system (3, 4).

Regionally focused studies from the NEH and adjacent hill ecosystems demonstrate that residue management, legume-based preceding crops and conservation tillage practices can markedly increase toria biomass, seed yield and oil quality traits by improving soil organic matter, available nitrogen-phosphorus-potassium (NPK) and soil microbial activity (3, 5). Given the NEH's fragmented landholdings, naturally acidic soils, low fertiliser use and dominance of rice-fallow or mixed cropping systems, identifying millet–legume-based sequences that enhance soil fertility and oilseed productivity has become a key research and development priority. Evaluating the residual effects of millet–legume preceding crops on toria performance, oil productivity (seed oil content and oil yield) and soil fertility indicators (available N, soil organic carbon and key enzyme

activities) can generate regionally relevant evidence needed to design sustainable and farmer-friendly cropping recommendations that enhance both livelihoods and agroecosystem resilience (1, 5).

In recent years, millet–legume intercropping and sequential systems have gained attention for their potential to enhance soil nutrient cycling, resource-use efficiency and crop diversification (6, 7). Millets contribute to improving soil structure and organic matter, while legumes enrich the soil through biological nitrogen fixation, reducing the dependence on chemical fertilisers (8, 9). Studies conducted in other agro-ecological regions of India have shown that legume-inclusive crop sequences increase subsequent crop yields by improving nutrient availability, root growth and soil microbial biomass (10, 11). However, systematic evaluations under the NEH's unique hill ecosystems characterised by high rainfall, steep slopes and fragile soils remain scarce. Consequently, there is a critical research gap regarding how different millet legume combinations as preceding crops influence toria's yield, oil content, fatty acid composition and post-harvest soil fertility in this region.

It was hypothesised that millet–legume-based cropping systems would exert a positive residual effect on toria by improving soil nutrient availability, soil organic carbon and biological activity compared with non-legume or sole millet systems. Consequently, these improvements in soil fertility were expected to enhance toria growth, seed yield, oil content and oil productivity under the rainfed hill conditions of the NEH Region.

The study aimed to quantify the residual influence of different millet–legume preceding crops on growth, productivity and oil quality of toria along with soil fertility indicators, while evaluating millet–legume sequences that optimise oilseed productivity and sustain soil health simultaneously. Furthermore, it was hypothesised that specific millet–legume sequences would perform better than others in sustaining soil health and productivity due to complementary nutrient cycling and enhanced resource-use efficiency.

Materials and Methods

Experimental site and climatic conditions

Field experiments were conducted during the rabi (winter) seasons of 2023–24 and 2024–25 at the Agricultural Farm, College of Agriculture, Kyrdekmlai, Umsning block, Ri-Bhoi district, Meghalaya, India (25°44'4.9" N latitude; 91°49'13.5" E longitude). The site falls under the Eastern Himalayan agro-climatic zone, characterised by undulating topography and a humid subtropical climate. The region receives moderate to high annual rainfall ranging from 200 to 400 cm, with temperatures during the cropping period varying between 4.1 °C and 24.4 °C. During the experimental seasons, relative humidity ranged from 61 to 87 %, while wind speed varied between 0.63 and 1.73 m sec⁻¹. Total rainfall recorded during the crop period was 41.93 mm, which was substantially lower than the cumulative potential evapotranspiration (310.54 mm), necessitating the application of supplemental irrigation.

The experimental soil was sandy in texture, comprising 62.2 % sand, 21.4 % silt and 16.4 % clay and was mildly acidic with a pH of 5.23. The soil exhibited an electrical conductivity of 0.22 dS m⁻¹, a cation exchange capacity of 16.5 cmol⁺ kg⁻¹ and an organic carbon content of 1.02 %, indicating moderate inherent fertility. Initial available macronutrient contents were 285.97 kg ha⁻¹ N, 13.23 kg ha⁻¹ P and 149.78 kg ha⁻¹ K.

Experimental design and treatments

Following the harvest of preceding millet–legume cropping sequences, toria (*Brassica rapa* var. *toria*) was cultivated to assess the residual effects of these sequences on crop performance, oil productivity and fatty acid composition. The experiment comprised 16 millet–legume treatment combinations (Table 1), laid out in a randomised block design (RBD) with 3 replications (Supplementary Fig. 1). The residual effects of the preceding cropping systems were maintained as experimental treatments (Supplementary Fig. 2). Each plot measured 3 m × 3 m (9 m²). Certified seed of toria variety 'M -27' was treated with thiram at 3 g kg⁻¹ seed prior to sowing to prevent seed-borne diseases. Sowing was carried out manually at a spacing of 30 cm between rows and 10 cm between plants, resulting in an approximate plant population of 333000 plants ha⁻¹. A shallow sowing depth of 1.5–2.0 cm was maintained to ensure uniform emergence under sandy soil conditions.

Table 1. Description of Treatments details preceding crop residue

Treatment number	Treatment description
T ₁	Sole finger millet
T ₂	Sole foxtail millet
T ₃	Sole soybean
T ₄	Sole green gram
T ₅	Soybean + Finger millet (1 : 1) additive series
T ₆	Soybean + Finger millet (1 : 2) additive series
T ₇	Soybean + Finger millet (1 : 1) replacement series
T ₈	Finger millet + Green gram (1 : 1) additive series
T ₉	Finger millet + Green gram (1 : 2) additive series
T ₁₀	Finger millet + Green gram (1 : 1) replacement series
T ₁₁	Soybean + Foxtail millet (1 : 1) additive series
T ₁₂	Soybean + Foxtail millet (1 : 2) additive series
T ₁₃	Soybean + Foxtail millet (1 : 1) replacement series
T ₁₄	Foxtail millet + Green gram (1 : 1) additive series
T ₁₅	Foxtail millet + Green gram (1 : 2) additive series
T ₁₆	Foxtail millet + Green gram (1 : 1) replacement series

Crop management practices

Fertilisers were applied at a uniform rate of 80 : 40 : 40 : 20 kg ha⁻¹ of N : P₂O₅ : K₂O : S, respectively. The entire dose of P, K and sulphur, along with 50 % of N, was applied as a basal dose at sowing, while the remaining 50 % N was top-dressed at 30 days after sowing (DAS).

Weed management was achieved through two manual weeding at approximately 30 and 60 DAS. Owing to inadequate rainfall during the crop growth period and high evapotranspiration demand, irrigations were applied at 15-day intervals to maintain optimum soil moisture. All agronomic practices were carried out uniformly across treatments and adapted to the humid subtropical conditions of the Eastern Himalayan region. Detailed information on sowing and harvesting dates, seed rate and treatment-wise fertiliser schedules is provided in Table 2.

Table 2. Agro-management details of toria cultivation during 2023–24 and 2024–25 crop seasons

Year	Sowing date	Harvesting date	Spacing (cm)	Seed rate (kg ha ⁻¹)	Variety	Doses of nutrients NPKS (kg ha ⁻¹)
2023–24	12.11.2023	11 Mar 2024	30 × 10	5.0	M-27	80–40–40–20
2024–25	5.11.2024	4 Mar 2025	30 × 10	5.0	M-27	80–40–40–20

Data collection

Growth and yield attributes

Growth and yield attributes were recorded at physiological maturity. Plant height (cm) was measured from the ground level to the tip of the main shoot and the number of primary branches per plant was counted from five randomly selected plants in each experimental plot. The same plants were used for recording yield-attributing parameters, namely the number of siliquae per plant, siliqua length (cm) and the number of seeds per siliqua. At harvest, seed yield was recorded from the net plot area after excluding the border rows to avoid border effects. The harvested seed yield was subsequently converted to kg ha⁻¹ and standardised at 10 % seed moisture content.

Seed yield and oil estimation

After harvest, toria seeds were cleaned, sun-dried and weighed to determine seed yield, which was expressed as kg ha⁻¹. Representative seed samples from each treatment were collected for oil content analysis.

The harvested seeds were further dried to attain a moisture content of approximately 8–9 % prior to oil extraction (12). Oil content was determined using the Soxhlet extraction method (13). Briefly, 10 g of finely ground seed sample was placed in a cellulose extraction thimble and extracted with analytical-grade n-hexane for 6 hr. Following extraction, the solvent was removed using a rotary evaporator at 40 °C under reduced pressure and the recovered oil was weighed. Oil content was calculated as a percentage of oven-dry seed weight using the following formula (14):

Oil content (%) =

$$\frac{\text{Weight of extracted oil}}{\text{Oven - dry Weight of seed sample}} \times 100 \quad \text{Eq. (1)}$$

Oil yield (kg ha⁻¹) was computed by multiplying seed yield (kg ha⁻¹) by oil content (%) and dividing by 100.

Oil yield (kg ha⁻¹) =

$$\frac{\text{Seed yield (kg ha}^{-1}\text{)} \times \text{Oil content (\%)}}{100} \quad \text{Eq. (2)}$$

Soil fertility analysis

Composite soil samples were collected from each experimental plot at a depth of 0–15 cm before sowing and after harvest of toria crop. The samples were air-dried under laboratory conditions, gently ground and passed through a 2-mm sieve to obtain a uniform sample for analysis. Available N was determined by the alkaline KMnO₄ distillation method described by Subbiah and Asija (15). Available P was estimated using Bray's method, which is suitable for acidic soils (16), while available K was measured with a flame photometer after extraction with neutral 1 N ammonium acetate (17). Soil organic carbon content was estimated following the Walkley and Black wet oxidation method (18). Soil pH and electrical

conductivity (EC) were measured in a 1 : 2.5 soil to water suspension using calibrated digital pH and conductivity meters, respectively (19).

Soil enzyme activities

Soil biological activity was evaluated through key enzyme associated with nutrient cycling and microbial functioning. Urease activity was measured based on the amount of ammonium (NH₄⁺) released following the hydrolysis of urea (20). Dehydrogenase activity was assessed by measuring the reduction of 2,3,5-triphenyltetrazolium chloride (TTC) to triphenyl formazan (TPF) (21). Protease activity was estimated by quantifying the hydrolysis of casein (22). These enzymes activities were used as sensitive indicators of soil biological health, nutrient transformation and organic matter decomposition processes.

Statistical analysis

All observations on growth parameters, yield components, seed yield, oil content, oil yield and soil chemical and biological properties were subjected to analysis of variance (ANOVA) appropriate for an RBD with 16 treatments and three replications. Treatment means were compared using Duncan's multiple range test (DMRT) at $p \leq 0.05$. Additionally, Pearson's correlation analysis was performed to examine relationships between soil fertility indicators and toria yield and oil traits. Principal component analysis (PCA) was employed to visualise treatment groupings and multivariate associations among soil variables. All statistical analyses were conducted using R software (R Core Team, 2024).

Results and Discussion

Growth, yield attributes and quality parameters

The residual effects of preceding millet-legume cropping systems significantly influenced the growth, yield attributes and quality parameters of toria during both cropping seasons (2023–24 and 2024–25). Distinct variations among treatments indicated a clear carry-over effect of different preceding crop combinations on the subsequent toria crop (Fig. 1 and 2, Table 3 and 4).

Plant height

During 2023–24, the tallest plants were observed under T₄ (sole green gram) with a plant height of 67.31 cm, which was statistically comparable with T₃ (sole soybean) (64.36 cm). The increased plant height under sole legume treatments may be attributed to improved residual soil nitrogen availability, enhanced nutrient mineralisation and better soil biological activity, which promoted vigorous vegetative growth of toria. In contrast, the lowest plant height was recorded under T₁₅ (foxtail millet + green gram, 1 : 2 additive series) (50.15 cm), followed by T₁₆ (foxtail millet + green gram, 1 : 1 replacement series) (50.83 cm). The comparatively lower plant height under these treatments could be associated with reduced residual nutrient availability and greater nutrient depletion by the preceding intercropping systems.

Table 3. Growth and yield attributes of toria as influenced by preceding millet–legume crops

Treatment	Plant height (cm)		Branches plant ⁻¹		Siliquae plant ⁻¹		Seeds siliqua ⁻¹	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
T ₁	56.25 ^{bc}	64.91 ^{cd}	4.42 ^{bc}	4.51 ^b	61.92 ^{ab}	61.86 ^c	6.73 ^{bc}	5.37 ^{bc}
T ₂	56.24 ^{bc}	64.93 ^{cd}	4.50 ^b	4.29 ^{bc}	59.58 ^{bc}	46.87 ^e	6.56 ^{bc}	5.61 ^{bc}
T ₃	64.36 ^{ab}	69.63 ^{ab}	4.30 ^{bc}	4.18 ^{bc}	57.69 ^c	68.16 ^a	7.19 ^{ab}	5.15 ^{bc}
T ₄	67.31 ^a	70.65 ^a	3.94 ^c	4.21 ^{bc}	57.31 ^c	58.15 ^{bc}	6.81 ^{bc}	5.57 ^{bc}
T ₅	59.80 ^b	66.23 ^{ab}	4.05 ^{bc}	4.14 ^{bc}	59.80 ^{bc}	68.63 ^a	5.85 ^{cd}	5.80 ^{bc}
T ₆	51.60 ^d	62.74 ^b	3.43 ^d	3.64 ^d	48.27 ^e	64.66 ^{ab}	6.26 ^{cd}	4.60 ^{cd}
T ₇	55.13 ^{bc}	68.84 ^a	3.82 ^{cd}	4.03 ^c	55.13 ^{cd}	54.40 ^{cd}	6.41 ^{cd}	5.24 ^{bc}
T ₈	56.90 ^{bc}	67.62 ^a	3.87 ^{cd}	3.54 ^d	56.90 ^{cd}	67.25 ^a	6.14 ^{cd}	5.35 ^{bc}
T ₉	55.53 ^{bc}	67.63 ^a	3.53 ^d	5.33 ^a	55.53 ^{cd}	50.39 ^d	6.84 ^{bc}	5.17 ^{bc}
T ₁₀	59.26 ^b	67.91 ^a	4.54 ^b	5.16 ^a	62.60 ^a	53.14 ^{cd}	5.97 ^{cd}	4.96 ^{cd}
T ₁₁	59.16 ^b	74.00 ^a	4.89 ^a	5.79 ^a	59.16 ^{bc}	74.00 ^a	7.61 ^a	5.50 ^{bc}
T ₁₂	54.73 ^{bc}	67.62 ^a	4.17 ^{bc}	5.41 ^a	54.73 ^d	58.20 ^{bc}	7.39 ^a	4.22 ^d
T ₁₃	52.09 ^{cd}	67.84 ^a	3.79 ^{cd}	4.45 ^b	52.09 ^{de}	67.84 ^a	7.28 ^a	4.13 ^d
T ₁₄	51.89 ^d	58.52 ^c	3.16 ^e	4.86 ^b	51.89 ^e	58.52 ^{bc}	7.31 ^a	4.60 ^{cd}
T ₁₅	50.15 ^d	66.63 ^{ab}	3.41 ^e	5.01 ^{ab}	50.15 ^e	66.63 ^a	7.24 ^a	4.69 ^{cd}
T ₁₆	50.83 ^d	58.98 ^c	2.85 ^e	4.74 ^b	47.49 ^e	58.98 ^{bc}	6.74 ^{bc}	4.93 ^{cd}

Means followed by the same superscript letter within a column are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test (DMRT).

Table 4. Seed yield, oil content and oil yield of toria as influenced by preceding millet–legume crops

Treatment	Seed yield (kg ha ⁻¹)		Oil content (%)		Oil yield (kg ha ⁻¹)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
T ₁	655.19 ^d	726.78 ^e	33.99 ^{bc}	33.61 ^{cd}	222.58 ^e	243.94 ^d
T ₂	649.61 ^d	715.57 ^e	34.35 ^{ab}	34.32 ^{bc}	223.05 ^e	246.04 ^d
T ₃	796.88 ^a	833.39 ^b	34.27 ^{ab}	34.62 ^a	273.23 ^a	287.74 ^a
T ₄	799.25 ^a	854.78 ^a	34.26 ^{ab}	34.14 ^{ab}	273.73 ^a	290.79 ^a
T ₅	758.62 ^b	802.96 ^c	34.26 ^{ab}	33.34 ^d	259.25 ^b	269.94 ^b
T ₆	702.21 ^c	788.13 ^d	33.64 ^{bc}	33.60 ^{cd}	236.37 ^c	265.29 ^{bc}
T ₇	681.50 ^c	796.56 ^c	33.94 ^{ab}	33.23 ^d	231.73 ^{cd}	264.45 ^{bc}
T ₈	704.59 ^c	815.71 ^b	33.27 ^{bc}	33.75 ^{bc}	233.28 ^c	275.26 ^b
T ₉	742.42 ^b	812.42 ^b	33.52 ^{bc}	34.62 ^a	249.65 ^b	281.27 ^b
T ₁₀	745.29 ^b	802.46 ^c	33.30 ^{bc}	33.68 ^{bc}	249.24 ^b	270.89 ^b
T ₁₁	744.79 ^b	776.69 ^d	32.68 ^c	33.76 ^{bc}	242.54 ^{bc}	262.36 ^{cd}
T ₁₂	673.73 ^c	784.60 ^d	33.19 ^{bc}	33.38 ^{cd}	223.47 ^e	261.68 ^{cd}
T ₁₃	674.68 ^c	779.55 ^d	33.36 ^{bc}	33.03 ^d	225.23 ^e	257.82 ^d
T ₁₄	689.59 ^c	783.63 ^d	32.86 ^c	33.01 ^d	226.11 ^e	258.23 ^d
T ₁₅	694.06 ^c	789.40 ^d	34.40 ^a	33.60 ^{cd}	239.14 ^{bc}	264.57 ^{bc}
T ₁₆	691.20 ^c	785.06 ^d	33.39 ^{bc}	33.67 ^{cd}	231.09 ^{cd}	264.79 ^{bc}

Means followed by the same superscript letter within a column are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test (DMRT).

A similar trend was observed during 2024–25, although plant height values were generally higher than those recorded in the previous year, indicating improved crop growth under favourable environmental conditions. The maximum plant height was recorded in T₁₁ (soybean + foxtail millet, 1 : 1 additive series) (74.00 cm), followed by T₄ (sole green gram) (70.65 cm). The minimum plant height was observed under T₁₄ (foxtail millet + green gram, 1 : 1 additive series) (58.52 cm) and T₁₆ (foxtail millet + green gram, 1 : 1 replacement series) (58.98 cm). The superior growth under soybean- and green gram-based systems might be due to greater residual nitrogen contribution and improved soil physico-biological conditions, which enhanced nutrient uptake and photosynthetic activity in the succeeding toria crop. This improvement is largely attributable to enhanced soil N and P availability, which are key drivers of vegetative growth, photosynthetic efficiency and reproductive development (23–27).

Number of branches per plant

The number of branches per plant varied significantly among treatments in both years. During 2023–24, the number of branches per plant ranged from 2.85 under T₁₆ (foxtail millet + green gram, 1 : 1 replacement series) to 4.89 under T₁ (sole finger millet). During 2024–25, the number of branches increased in most treatments, ranging

from 3.54 under T₈ (finger millet + green gram, 1 : 1 additive series) to 5.79 under T₁₁ (sole finger millet). Treatments T₁₁ (soybean + foxtail millet, 1 : 1 additive series), T₁₀ (finger millet + green gram, 1 : 1 replacement series) and T₁₂ (soybean + foxtail millet, 1 : 2 additive series) consistently produced a higher number of branches per plant during both seasons. Adequate nutrient availability promotes lateral bud growth and assimilates partitioning towards secondary shoots (28, 35, 36). Conversely, nutrient stress often results in hormonal imbalance and assimilate limitation, suppressing branch initiation (23, 37). Nitrogen, being a structural component of chlorophyll, amino acids and enzymes, enhances photosynthesis and biomass accumulation, while P supports ATP synthesis, root growth and reproductive organ differentiation (24, 25, 28). Similar yield advantages of legume-based rotations have been widely reported due to biological N fixation and improved nutrient cycling (29, 30).

Number of siliquae per plant

During 2023–24, the highest number of siliquae per plant was recorded under T₁₀ (finger millet + green gram, 1 : 1 replacement series) (62.60), followed by T₁ (sole finger millet) (61.92), whereas the lowest number was observed under T₁₆ (foxtail millet + green gram, 1 : 1 replacement series) (47.49).

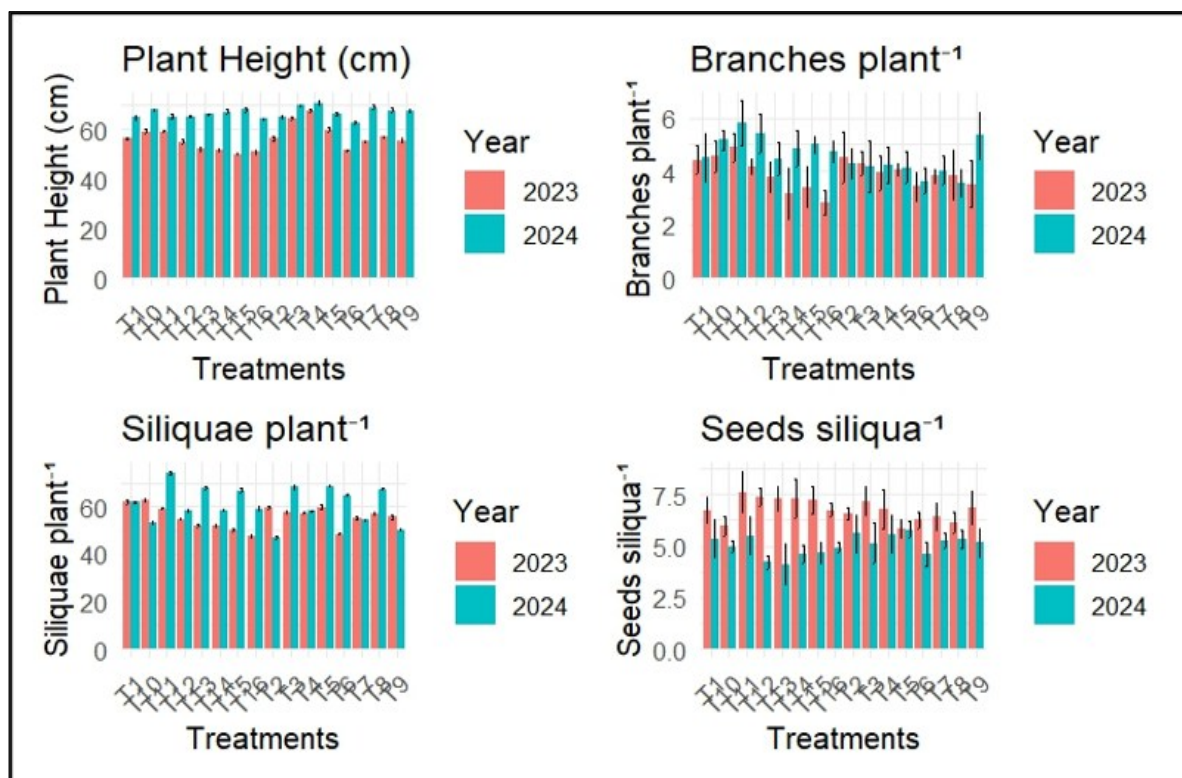


Fig. 1. Comparison of toria crop growth and yield attributes (plant height, branches per plant, siliquae per plant, seeds per siliqua) across treatments and years (2023 vs 2024), illustrating the impact of different cropping interventions on plant performance.

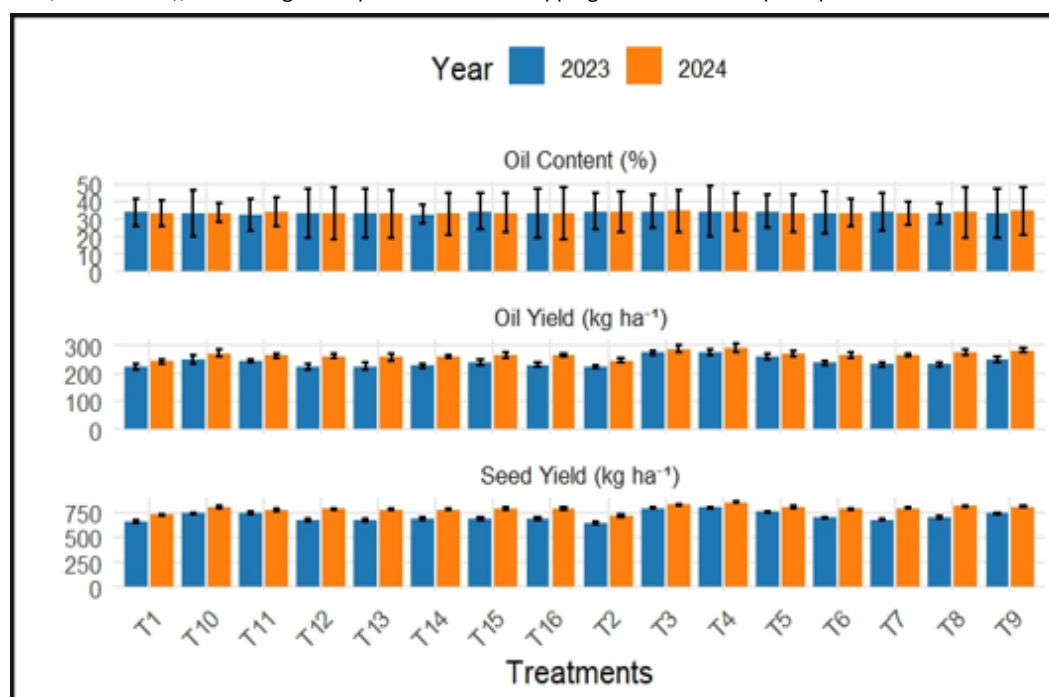


Fig. 2. Comparison of seed yield, oil content and oil yield across different treatments in 2023 and 2024. The bar graph illustrates the residual impact of preceding millet–legume cropping interventions on toria performance, highlighting treatment-wise variations in crop productivity and quality traits.

During 2024–25, the number of siliquae per plant increased in most treatments. The maximum number of siliquae was recorded under T₁₁ (soybean + foxtail millet, 1 : 1 additive series) (74.00), while the minimum was observed under T₂ (sole foxtail millet) (46.87).

Number of seeds per siliqua

During 2023–24, higher numbers of seeds per siliqua were recorded under T₁₁ (soybean + foxtail millet, 1 : 1 additive series) (7.61), followed by T₁₂ (soybean + foxtail millet, 1 : 2 additive series) (7.39) and T₁₃ (soybean + foxtail millet, 1 : 1 replacement series) (7.28). The

lowest number of seeds per siliqua was observed under T₅ (soybean + finger millet, 1 : 1 additive series) (5.85).

During 2024–25, a slight reduction in the number of seeds per siliqua was observed across most treatments. Moderate values were recorded under T₅ (soybean + finger millet, 1 : 1 additive series) (5.80), T₂ (sole foxtail millet) (5.61) and T₁ (sole finger millet) (5.37). However, treatments T₁₁, T₁₂ and T₁₃ continued to maintain comparatively higher numbers of seeds per siliqua during the second year as well.

Yield-contributing traits such as number of siliquae per plant and seeds per silique were markedly higher under treatments with improved soil fertility (T_{10} – T_{13}). Phosphorus and K are especially critical during flowering and seed filling stages, influencing pollen viability, fertilisation efficiency and seed development (24, 25, 33, 38). Additionally, the relatively cool winter temperatures and residual soil moisture of the NEH Region may have prolonged the reproductive phase of toria, further supporting higher seed set under fertile rotations (27, 39).

Seed yield (kg ha⁻¹)

Seed yield of toria differed significantly among the treatments during both years of experimentation, indicating the pronounced residual influence of millet–legume-based cropping systems on crop productivity.

During 2023–24, the highest seed yield was recorded under T_4 (sole green gram) (799.25 kg ha⁻¹), which was closely followed by T_3 (sole soybean) (796.88 kg ha⁻¹). These treatments produced significantly higher yields compared to T_2 (sole foxtail millet) (649.61 kg ha⁻¹) and T_1 (sole finger millet) (655.19 kg ha⁻¹). The higher seed yield under sole legume-based systems may be attributed to improved residual soil fertility, particularly enhanced nitrogen availability, better nutrient recycling and increased biological activity, which collectively promoted better growth and yield attributes of the succeeding toria crop.

A similar trend was observed during 2024–25. The maximum seed yield was again recorded under T_4 (sole green gram) (854.78 kg ha⁻¹), followed by T_3 (sole soybean) (833.39 kg ha⁻¹). Among the intercropping systems, T_8 (finger millet + green gram, 1 : 1 additive series) (815.71 kg ha⁻¹) and T_9 (finger millet + green gram, 1 : 2 additive series) (812.42 kg ha⁻¹) also produced comparatively higher seed yields. In contrast, the lowest seed yields were recorded under T_1 (sole finger millet) (726.78 kg ha⁻¹) and T_2 (sole foxtail millet) (715.57 kg ha⁻¹). The superior performance of legume-based systems might be due to their beneficial residual effects on soil physico-chemical and biological properties, resulting in enhanced nutrient uptake, improved photosynthetic efficiency and better partitioning of assimilates towards seed development in toria.

These findings confirm that legume-based millet rotations synergistically improve vegetative vigour, reproductive efficiency and seed yield of toria, primarily through enhanced nutrient availability, improved soil organic carbon and stimulated microbial activity. This aligns well with earlier reports highlighting the sustainability benefits of cereal–legume systems in marginal soils (30, 31, 34, 40).

Oil content (%)

Oil content of toria seeds exhibited moderate variation among the treatments during both years of experimentation, indicating that the residual effects of preceding cropping systems influenced seed quality to some extent.

During 2023–24, the highest oil content was recorded under T_{15} (foxtail millet + green gram, 1 : 2 additive series) (34.40 %), followed closely by T_2 (sole foxtail millet) (34.35 %). In contrast, the lowest oil content was observed under T_{11} (soybean + foxtail millet, 1 : 1 additive series) (32.68 %) and T_{14} (foxtail millet + green gram, 1 : 1 additive series) (32.86 %). The relatively higher oil content under certain foxtail millet-based systems may be associated with balanced nutrient availability and favourable assimilate partitioning towards oil synthesis in seeds.

During 2024–25, oil content ranged from 33.01 % under T_{14} (foxtail millet + green gram, 1 : 1 additive series) to 34.62 % under T_3 (sole soybean). The comparatively higher oil content under soybean-based systems might be attributed to improved residual N dynamics and enhanced metabolic activity, which could have favoured lipid biosynthesis in the succeeding toria crop.

Oil yield (kg ha⁻¹)

Oil yield of toria was significantly influenced by the preceding cropping systems and largely followed trends similar to seed yield during both years.

During 2023–24, the maximum oil yield was recorded under T_4 (sole green gram) (273.73 kg ha⁻¹), closely followed by T_3 (sole soybean) (273.23 kg ha⁻¹). The higher oil yield under these treatments was mainly due to their superior seed yield coupled with comparatively higher oil content. In contrast, the minimum oil yield was observed under T_1 (sole finger millet) (222.58 kg ha⁻¹) and T_2 (sole foxtail millet) (223.05 kg ha⁻¹).

A similar trend was observed during 2024–25, wherein T_4 (sole green gram) recorded the highest oil yield (290.79 kg ha⁻¹), followed by T_3 (sole soybean) (287.74 kg ha⁻¹). The enhanced oil yield under legume-based systems may be attributed to improved residual soil fertility, greater nutrient availability and better crop growth, which collectively contributed to increased seed production and oil accumulation in toria seeds.

Soil physico-chemical properties

The residual effects of preceding millet–legume cropping systems on soil physico-chemical properties over two consecutive years (2023–24 and 2024–25) are presented in Table 5 and Fig. 3. Noticeable differences were observed among treatments under the acidic soil conditions of the Khasi Hills Region.

Soil pH

Soil pH remained acidic under all treatments during both years of experimentation, ranging from 5.280 to 5.430. Despite the narrow variation, significant differences among treatments were observed. The highest soil pH was recorded under T_8 (finger millet + green gram, 1 : 1 additive series) (5.420–5.430), whereas the lowest pH was observed under T_{14} (foxtail millet + green gram, 1 : 1 additive series) (5.280–5.290). In general, treatments involving millet–legume intercropping systems maintained slightly higher soil pH compared to sole millet cropping systems. This improvement may be attributed to enhanced organic matter addition, biological nitrogen fixation and release of basic cations through decomposition of legume residues, which helped moderate soil acidity. Such marginal pH moderation is agronomically meaningful in acidic soils, where aluminum toxicity and nutrient fixation constrain crop productivity. Organic matter additions from legume residues can neutralize soil acidity by releasing basic cations (Ca^{2+} , Mg^{2+} and K^+) during decomposition and by complexing exchangeable Al^{3+} ions (29, 31–33).

Soil organic carbon (%)

Soil organic carbon (SOC) content varied significantly among the treatments during both years. During 2023–24, SOC content ranged from 1.016 % to 1.263 %, whereas during 2024–25 it ranged from 1.173 % to 1.227 %. The highest SOC content was consistently recorded under T_3 (sole soybean), while the lowest values were observed under T_1 (sole finger millet). Treatments such as T_3 (sole soybean), T_4 (sole green gram), T_5 (soybean + finger millet, 1 : 1

Table 5. Soil pH, organic carbon and electrical conductivity (EC) under toria as influenced by preceding millet–legume crops

Treatment	pH		Organic Carbon (%)		EC (dS m ⁻¹)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
T ₁	5.32 ^a	5.33 ^a	1.07 ^d	1.02 ^e	0.18 ^c	0.19 ^b
T ₂	5.39 ^{ab}	5.40 ^{ab}	1.08 ^{cd}	1.01 ^e	0.19 ^{bc}	0.20 ^{ab}
T ₃	5.36 ^a	5.37 ^a	1.26 ^b	1.23 ^b	0.19 ^{bc}	0.21 ^a
T ₄	5.36 ^a	5.37 ^a	1.26 ^b	1.20 ^c	0.18 ^c	0.19 ^b
T ₅	5.38 ^{ab}	5.39 ^{ab}	1.26 ^b	1.19 ^{cd}	0.21 ^{ab}	0.22 ^a
T ₆	5.36 ^a	5.37 ^a	1.21 ^c	1.19 ^d	0.20 ^b	0.20 ^{ab}
T ₇	5.39 ^{ab}	5.40 ^{ab}	1.25 ^b	1.17 ^e	0.22 ^a	0.20 ^{ab}
T ₈	5.42 ^b	5.43 ^b	1.23 ^{bc}	1.20 ^{cd}	0.21 ^{ab}	0.19 ^b
T ₉	5.31 ^a	5.32 ^a	1.25 ^b	1.21 ^b	0.20 ^b	0.21 ^a
T ₁₀	5.42 ^b	5.43 ^b	1.24 ^{bc}	1.18 ^e	0.20 ^b	0.20 ^{ab}
T ₁₁	5.40 ^{ab}	5.41 ^{ab}	1.26 ^b	1.18 ^e	0.19 ^{bc}	0.19 ^b
T ₁₂	5.36 ^a	5.37 ^a	1.23 ^{bc}	1.19 ^d	0.19 ^{bc}	0.20 ^{ab}
T ₁₃	5.39 ^{ab}	5.40 ^{ab}	1.24 ^b	1.20 ^c	0.21 ^{ab}	0.18 ^c
T ₁₄	5.28 ^a	5.29 ^a	1.25 ^b	1.21 ^b	0.20 ^b	0.19 ^b
T ₁₅	5.32 ^a	5.33 ^a	1.22 ^c	1.19 ^d	0.20 ^b	0.19 ^b
T ₁₆	5.33 ^a	5.34 ^a	1.22 ^c	1.19 ^d	0.21 ^{ab}	0.18 ^c

Means followed by the same superscript letter within a column are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test (DMRT).

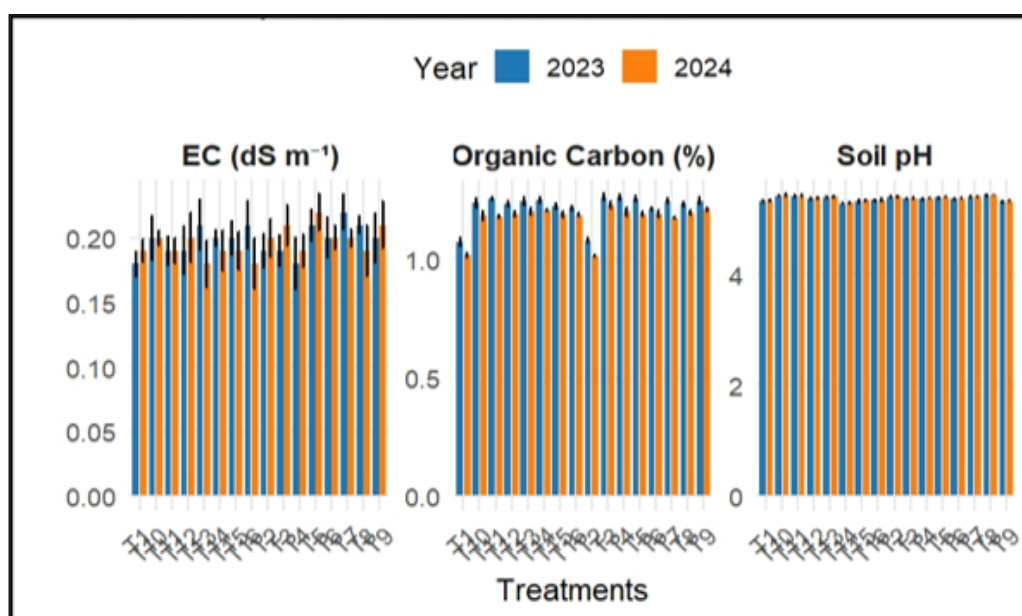


Fig. 3. Comparison of soil physico-chemical properties pH, electrical conductivity (EC) and organic carbon (OC) across different treatments after toria cultivation in 2023 and 2024. The bar graph highlights the influence of preceding millet–legume cropping systems on soil fertility and quality.

additive series), T₇ (soybean + finger millet, 1 : 1 replacement series), T₉ (finger millet + green gram, 1 : 2 additive series), T₁₁ (soybean + foxtail millet, 1 : 1 additive series) and T₁₄ (foxtail millet + green gram, 1 : 1 additive series) recorded significantly higher SOC levels compared to sole cropping systems. Legumes contribute higher biomass inputs, finer roots and more labile residues that decompose rapidly, enhancing microbial activity, aggregation and humus formation (27, 30, 32). Increased SOC also plays a critical role in improving nutrient availability, moisture retention and soil structural stability in acid upland soils.

Electrical conductivity

Soil EC remained low and relatively uniform across all treatments, ranging from 0.18 to 0.22 dS m⁻¹ during both years. Slightly higher EC values were observed under T₇ (soybean + finger millet, 1 : 1 replacement series) and T₅ (soybean + finger millet, 1 : 1 additive series), whereas the lowest EC was recorded under T₁ (sole finger millet). However, all EC values remained within the non-saline range, indicating the absence of harmful salt accumulation under any of the cropping systems. The EC remained uniformly low across

treatments, indicating the absence of salinity hazards. The high rainfall regime and efficient leaching typical of the NEH uplands prevent salt accumulation, even under intensified cropping (34, 40).

Soil available nutrients

The residual effects of preceding cropping systems on soil available N, P and K are presented in Table 6 and Fig. 4. Significant differences among treatments were observed during both years, indicating the beneficial influence of legume-based systems on soil nutrient dynamics.

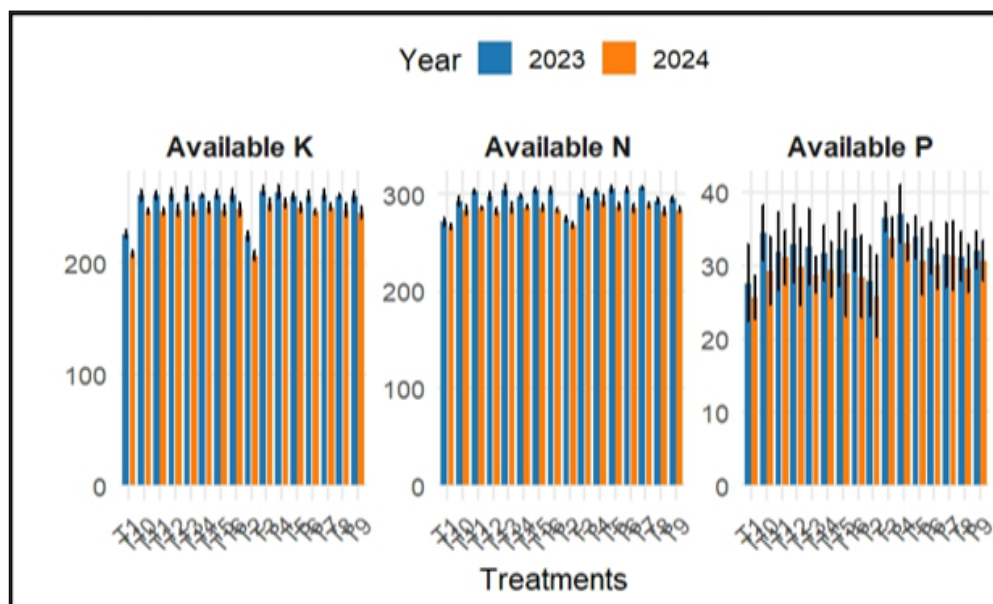
Available nitrogen (kg ha⁻¹)

Soil available N ranged from 271.15 to 306.18 kg ha⁻¹ during 2023–24 and from 266.50 to 292.92 kg ha⁻¹ during 2024–25. The highest available N content was recorded under T₇ (soybean + finger millet, 1 : 1 replacement series) (306.18 kg ha⁻¹) during 2023–24, followed by T₅ (soybean + finger millet, 1 : 1 additive series) and T₆ (soybean + finger millet, 1 : 2 additive series). The lowest available N was observed under T₁ (sole finger millet) (271.15 kg ha⁻¹). Treatments incorporating legumes, namely T₃, T₄, T₅, T₆, T₇, T₁₃, T₁₅ and T₁₆,

Table 6. Soil available nitrogen (N), phosphorus (P) and potassium (K) under as influenced by preceding millet-legume crops (2023–24 and 2024–25)

Treatment	Available N (kg ha ⁻¹)		Available P (kg ha ⁻¹)		Available K (kg ha ⁻¹)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
T ₁	271.15 ^c	266.50 ^d	27.58 ^e	25.64 ^e	226.11 ^d	208.73 ^e
T ₂	274.09 ^c	267.38 ^d	27.86 ^e	25.79 ^e	224.68 ^d	207.01 ^e
T ₃	300.13 ^b	290.14 ^b	36.56 ^a	33.81 ^a	265.20 ^a	252.99 ^a
T ₄	302.44 ^b	292.92 ^b	37.00 ^a	33.12 ^a	264.15 ^a	254.29 ^a
T ₅	305.22 ^a	287.27 ^b	33.82 ^b	30.57 ^b	259.84 ^b	250.10 ^b
T ₆	303.55 ^a	285.70 ^b	32.36 ^b	30.14 ^b	260.30 ^b	246.21 ^b
T ₇	306.18 ^a	288.17 ^b	31.42 ^c	31.32 ^b	261.20 ^b	250.39 ^b
T ₈	292.85 ^b	282.29 ^c	31.23 ^c	29.60 ^c	259.86 ^b	247.72 ^b
T ₉	294.43 ^b	283.77 ^c	32.08 ^b	30.56 ^b	259.77 ^b	245.34 ^b
T ₁₀	292.63 ^b	283.09 ^c	34.50 ^b	29.24 ^c	261.08 ^b	246.58 ^b
T ₁₁	302.61 ^b	285.59 ^b	31.91 ^c	31.08 ^b	261.04 ^b	246.54 ^b
T ₁₂	297.32 ^b	281.79 ^c	32.92 ^b	29.72 ^b	262.02 ^b	248.02 ^b
T ₁₃	303.74 ^a	285.87 ^b	32.45 ^b	28.65 ^c	262.83 ^b	248.23 ^b
T ₁₄	297.39 ^b	286.56 ^b	31.68 ^c	29.43 ^b	260.93 ^b	249.79 ^b
T ₁₅	304.06 ^a	286.17 ^b	32.21 ^b	28.89 ^c	261.85 ^b	247.30 ^b
T ₁₆	303.55 ^a	283.47 ^c	33.77 ^b	28.44 ^c	261.22 ^b	248.39 ^b

Means followed by the same superscript letter within a column are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test (DMRT).

**Fig. 4.** Treatment-wise comparison of soil available nutrients nitrogen (N), phosphorus (P) and potassium (K) after toria cultivation in 2023 and 2024. The bar graph illustrates the residual effects of preceding millet-legume cropping systems on soil nutrient status.

maintained significantly higher available nitrogen compared to sole millet systems. The enhanced N availability under legume-based systems may be attributed to biological N fixation and improved organic matter decomposition. Higher soil N under legume-based treatments primarily resulted from symbiotic biological nitrogen fixation and the mineralisation of N-rich residues, which contributed sustained N availability to the succeeding toria crop (30, 41).

Available phosphorus (kg ha⁻¹)

Available P content ranged from 27.58 to 37.00 kg ha⁻¹ during 2023–24 and from 25.64 to 33.81 kg ha⁻¹ during 2024–25. The highest P content was recorded under T₄ (sole green gram) (37.00 kg ha⁻¹), followed closely by T₃ (sole soybean) (36.56 kg ha⁻¹), both of which were significantly superior to other treatments. Moderate phosphorus levels were observed under T₅, T₆, T₁₀ and T₁₂, whereas the lowest available P was recorded under T₁ (sole finger millet) and T₂ (sole foxtail millet). The higher P availability under legume-based systems might be due to organic acid secretion by roots and enhanced microbial solubilisation of native soil P. Soil P availability

was also greater under legume-inclusive rotations. Legume root exudates, organic acids and phosphatase enzymes promote the solubilisation of P bound to Fe and Al oxides in acidic soils (25, 33, 42). While P fixation remains a constraint in such soils, the presence of legumes clearly improved P bioavailability relative to sole millet systems.

Available potassium (kg ha⁻¹)

Soil available K ranged from 224.68 to 265.20 kg ha⁻¹ during 2023–24 and from 207.01 to 254.29 kg ha⁻¹ during 2024–25. The highest K levels were observed under T₃ (sole soybean) and T₄ (sole green gram), while the lowest values were recorded under T₁ (sole finger millet) and T₂ (sole foxtail millet). The remaining treatments recorded intermediate K values. The relatively higher K availability under legume-based systems may be associated with improved organic matter content and enhanced nutrient recycling through decomposition of crop residues. Decomposition of millet residues and increased root activity facilitate the release of non-exchangeable K through mineral weathering and nutrient recycling (27, 31).

In contrast, continuous millet cultivation depleted soil K due to high crop removal without adequate replenishment (37). These findings corroborate earlier reports that cereal-legume rotations slow nutrient mining, enhance nutrient recycling and sustain soil fertility compared to monocropping systems (30, 33, 42).

Soil enzyme activities

Soil enzyme activities varied significantly among treatments during both years, reflecting differences in soil biological activity under various millet-legume-based cropping systems (Fig. 5 and 6, Table 7).

Urease activity

Urease activity ranged from 24.97 to 27.97 $\mu\text{g NH}_4^+ \text{g}^{-1} \text{soil h}^{-1}$ during the study period. The highest urease activity was recorded under T₁₃ (soybean + foxtail millet, 1 : 1 replacement series) (27.97), followed by T₉ (finger millet + green gram, 1 : 2 additive series) (27.88) and T₃ (sole soybean) (27.70). Lower urease activity was observed under T₁ (sole finger millet) (25.94) and T₂ (sole foxtail millet) (25.46). Although a slight reduction in urease activity was noticed during 2024–25,

legume-based treatments consistently maintained higher enzyme activity, possibly due to greater microbial proliferation and increased substrate availability from crop residues. Elevated urease activity reflects greater availability of organic N substrates from legume residues, stimulating urea hydrolysis and ammonium production (33, 38).

Protease activity

Protease activity ranged from 14.06 to 16.18 $\mu\text{g Tyr g}^{-1} \text{soil hr}^{-1}$. The highest activity was recorded under T₁₃ (soybean + foxtail millet, 1 : 1 replacement series) (16.18), followed by T₉ (finger millet + green gram, 1 : 2 additive series) (16.06). Lower protease activity was observed under continuous millet-based systems such as T₁ and T₂. The increased activity under legume-based systems may be attributed to higher organic N inputs and enhanced microbial metabolism in the rhizosphere. Similarly, higher protease activity under legume-based treatments signifies accelerated protein degradation and N mineralisation, driven by N-rich organic inputs (40, 43).

Table 6. Soil available nitrogen (N), phosphorus (P) and potassium (K) under as influenced by preceding millet-legume crops (2023–24 and 2024–25)

Treatment	Urease ($\mu\text{g NH}_4^+ \text{g}^{-1} \text{soil hr}^{-1}$)		Protease ($\mu\text{g Tyr g}^{-1} \text{soil hr}^{-1}$)		Dehydrogenase ($\mu\text{g TPF g}^{-1} \text{soil 24 hr}^{-1}$)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
T ₁	25.94 ^d	24.97 ^d	14.49 ^d	14.11 ^d	112.50 ^e	105.48 ^e
T ₂	25.46 ^d	25.14 ^d	14.06 ^d	14.29 ^d	113.27 ^e	106.76 ^e
T ₃	27.70 ^{ab}	26.71 ^{ab}	15.97 ^{ab}	15.80 ^{ab}	130.33 ^a	123.91 ^a
T ₄	27.27 ^{bc}	26.29 ^{bc}	15.67 ^b	15.57 ^b	131.24 ^a	123.14 ^a
T ₅	26.55 ^c	26.94 ^{ab}	14.91 ^c	15.46 ^{bc}	127.76 ^b	118.42 ^b
T ₆	26.67 ^{bc}	26.83 ^{ab}	15.06 ^c	15.57 ^b	129.52 ^{ab}	120.74 ^{ab}
T ₇	27.09 ^{bc}	27.03 ^{ab}	15.46 ^b	15.74 ^b	128.96 ^b	117.70 ^{bc}
T ₈	27.55 ^{ab}	27.29 ^{ab}	15.79 ^{ab}	15.89 ^{ab}	126.10 ^{bc}	118.67 ^b
T ₉	27.88 ^a	27.43 ^a	16.06 ^a	16.03 ^a	127.48 ^b	118.12 ^b
T ₁₀	27.18 ^{bc}	27.14 ^{ab}	15.61 ^b	15.74 ^b	127.70 ^b	119.42 ^b
T ₁₁	27.36 ^{ab}	27.20 ^{ab}	15.73 ^{ab}	15.80 ^{ab}	125.51 ^{bc}	119.58 ^b
T ₁₂	26.82 ^c	27.03 ^{ab}	15.24 ^c	15.63 ^b	126.59 ^{bc}	120.13 ^b
T ₁₃	27.97 ^a	26.86 ^{ab}	16.18 ^a	15.71 ^b	127.48 ^b	118.70 ^b
T ₁₄	27.64 ^{ab}	26.54 ^{bc}	15.97 ^{ab}	15.57 ^b	123.91 ^{cd}	120.83 ^{ab}
T ₁₅	27.18 ^{bc}	26.71 ^{ab}	15.61 ^b	15.63 ^b	129.72 ^{ab}	120.66 ^{ab}
T ₁₆	26.97 ^{bc}	26.94 ^{ab}	15.39 ^c	15.74 ^b	127.37 ^b	120.30 ^{ab}

Means followed by the same superscript letter within a column are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test (DMRT).

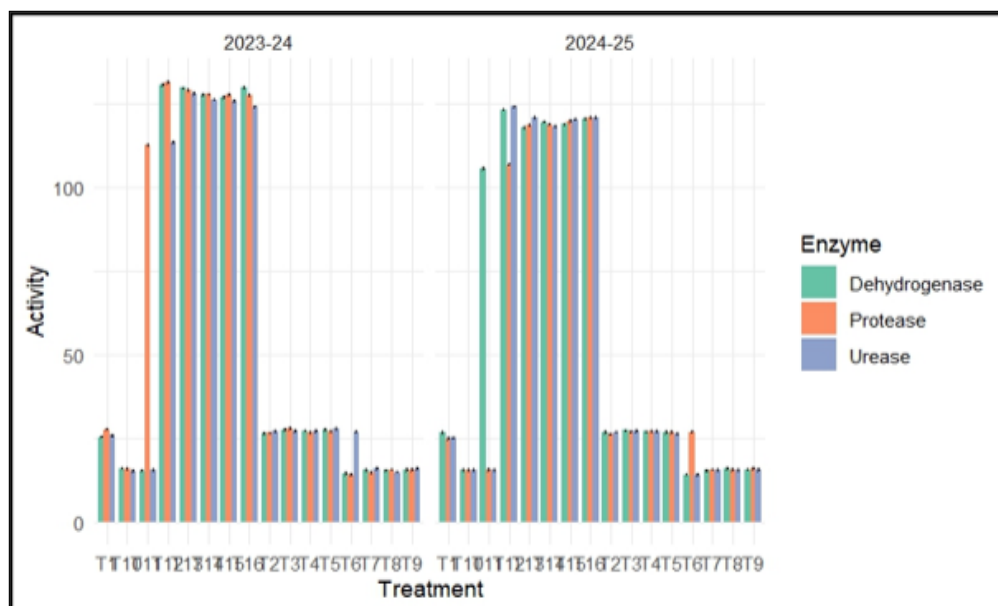


Fig. 5. Comparison of soil enzyme activities, urease, protease and dehydrogenase across different treatments after toria cultivation in 2023 and 2024. The bar graph highlights the residual impact of preceding millet-legume cropping systems on soil biological activity and fertility.

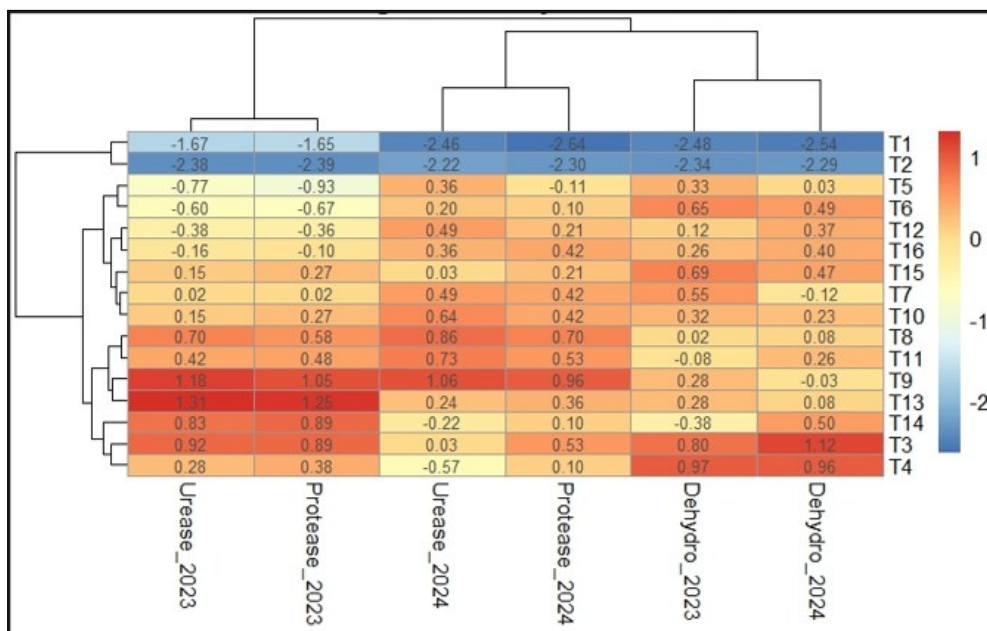


Fig. 6. Heatmap and hierarchical clustering of soil enzymatic activities (urease, protease, dehydrogenase) for different treatments across two years, showing variations and similarities among samples by colour intensity and dendrogram structure.

Dehydrogenase activity

Dehydrogenase activity ranged from 105.48 to 131.24 $\mu\text{g TPF g}^{-1}$ soil 24 hr^{-1} during the experimental period. The maximum dehydrogenase activity was recorded under T₄ (sole green gram) (131.24), followed closely by T₃ (sole soybean) (130.33), whereas the minimum activity was observed under T₁ (sole finger millet) (105.48) and T₂ (sole foxtail millet) (106.76). Higher dehydrogenase activity under legume-based treatments indicates enhanced microbial respiration and greater biological activity resulting from improved soil organic matter and nutrient availability. Increased dehydrogenase activity under legume-inclusive systems highlights enhanced microbial respiration and overall metabolic activity, supported by carbon-rich root exudates and residues (39, 44). Continuous millet monocropping, in contrast, returned limited organic substrates to the soil, resulting in reduced microbial activity and enzyme production (27, 37).

Although a slight decline in enzyme activity was observed in the second year for some treatments, legume-based systems consistently maintained higher biological activity than monocultures. Since soil enzymes are sensitive indicators of soil health and fertility, their enhancement under millet-legume rotations underscore the importance of legumes in sustaining soil biological functions and long-term agroecosystem productivity (30, 38, 40).

Principal component analysis

Principal component analysis of soil fertility and enzyme activity data revealed that the first two principal components explained 79.0 % of the total variability (Dim1: 66.8 %; Dim2: 12.2 %) (Fig. 7). Three distinct treatment clusters were identified. Cluster 1 was associated with higher enzymatic activities, organic carbon and potassium. Cluster 2 exhibited intermediate variation along Dim1, while Cluster 3 was associated with higher soil pH, EC and available P. Dim1 was primarily influenced by biological indicators and organic carbon, whereas Dim2 reflected variation in soil chemical properties.

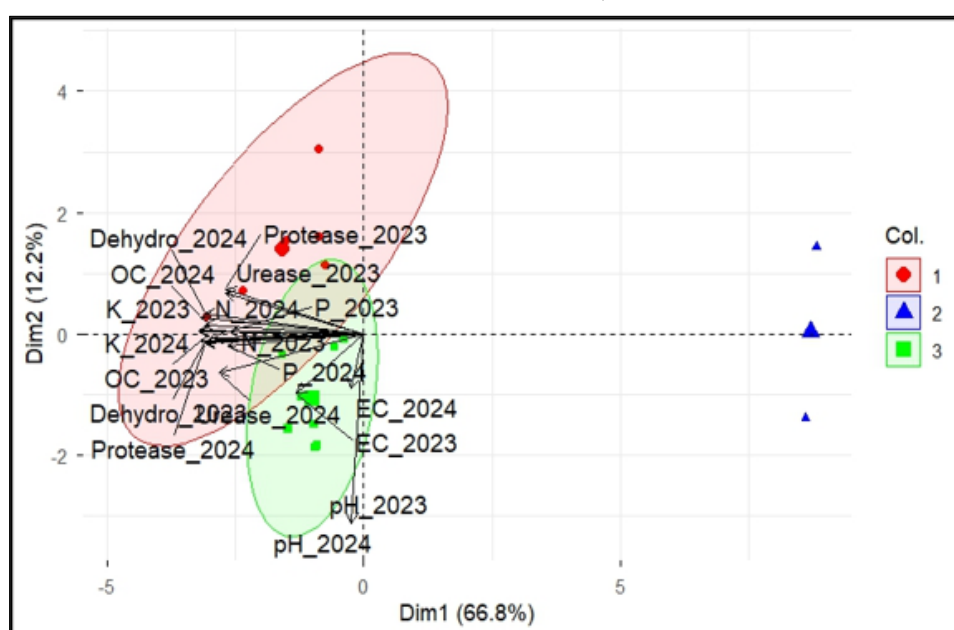


Fig. 7. Principal component analysis (PCA) biplot illustrating the clustering of soil fertility and enzyme activity parameters for different years and variables, with clusters grouped by colour and shape to highlight distinctions among sample sets.

Conclusion

Millet legume crop rotations markedly improved toria growth, yield and oil productivity in the acidic, nutrient-limited soils of the NEH uplands. Legume-inclusive sequences enhanced key vegetative and reproductive traits of toria plant height, branching, siliqua number and seed count through improved nutrient availability, particularly nitrogen (N), phosphorus (P) and sulfur. Soil quality parameters, including pH, organic carbon and macronutrient levels [(N, P and potassium (K)], were positively influenced under diversified rotations. Elevated urease, protease and dehydrogenase activities in soil further reflected enhanced microbial activity and efficient nutrient cycling in legume-based systems. Collectively, these improvements led to better nutrient uptake, assimilate partitioning and reproductive success in toria. Beyond immediate yield gains, diversified millet-legume rotations helped mitigate soil acidity, build soil organic matter and maintain soil fertility while strengthening soil-plant-microbe interactions, thus demonstrating greater resilience under rainfed conditions. Overall, integrating millets and legumes offers a sustainable and ecologically sound strategy for intensifying oilseed production, optimising resource-use efficiency and securing smallholder livelihoods in fragile upland ecosystems. Adoption of such cropping systems provides a practical pathway for sustainable agricultural intensification in the North-East Hill (NEH) Region by balancing productivity with soil health and environmental stewardship.

Acknowledgements

The authors are grateful to the School of Natural Resources Management, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya, where the research was carried out and to the Professor and Head, Department of Agronomy, for providing the necessary facilities and support for the preparation of the initial draft of the manuscript.

Authors' contributions

AK carried out the experiment, recorded the observations and analysed the data. BY and VR formulated the research concept and guided the study. SS, LIPR and RH participated in the study design, performed the statistical analysis and reviewed the manuscript. KZ, DKM and PK contributed to conducting the experiment and helped edit, summarise and revise the manuscript. MBR and AT also helped summarise and revise the manuscript. AK and AKS approved the final manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

References

- Amrutha D, Ramesh T, Kumar N. Millets as a resilient base crop for diversified intercropping under stress-prone ecologies. *Int J Agron Plant Prod.* 2024;52(1):55–69.
- Singh S, Devi NB, Divya D, Kumar A, Singh S, Tyagi G, et al. Soil fertility management: role of organic amendments and bio-fertilizers: a review. *Int J Res Agron.* 2024;7(12):766–72. <https://doi.org/10.33545/2618060X.2024.v7.i12j.2253>
- Das A, Ghosh PK, Verma MR, Munda GC, Ngachan SV, Mandal D. Tillage and residue mulching effect on productivity of maize-toria cropping system in fragile ecosystem of Northeast Indian Himalayas. *Exp Agric.* 2014;50(1):103–25. <https://doi.org/10.1017/S0014479714000179>
- Chaudhary A, Meena MC, Bana RS, Dey A, Datta SP, Mahala D, et al. Effectiveness of zero tillage and legume-based cropping systems on soil nitrogen under rainfed pearl millet. *J Indian Soc Soil Sci.* 2023;71(3):299–308. <https://doi.org/10.5958/0974-0228.2023.00028.2>
- Kuotsu K, Munda GC, Das A, Verma BC. Soil health as affected by land configuration and conservation tillage in groundnut-toria system. *Indian J Agric Sci.* 2009;79(11):853–7.
- Chaudhary SK, Mandal B, Malakar P, Sarkar A. Growth and dry matter accumulation of pearl millet under cowpea-based intercropping. *J Crop Weed.* 2020;16(3):142–9.
- Kumar R, Meena RS, Lal R, Yadav GS, Singh VK. Biological nitrogen fixation and soil nitrogen replenishment in cereal-legume intercropping systems. *Arch Agron Soil Sci.* 2021;66(12):1671–85.
- Subrahmaniyan K, Veeramani P. Heat accumulation effects on phenology, fibre yield and properties of sunnhemp genotypes. *J Integr Agric.* 2021;20(9):2395–409. [https://doi.org/10.1016/S2095-3119\(20\)63357-3](https://doi.org/10.1016/S2095-3119(20)63357-3)
- Singh P, Kumar R, Meena RS, Lal B. Influence of intercropping on soil biological activity and crop growth under rainfed conditions. *Arch Agron Soil Sci.* 2023;69(8):1185–98.
- Mondal D, Routray BK, Pattanaik BR, Majhi P, Mohanty AK. Yield enrichment of toria through frontline demonstration in coastal Odisha. *J Pharmacogn Phytochem.* 2020;9(5):2360–2.
- Meena RS, Kumar R, Mehta RS, Lal B. Canopy stratification and light interception in sorghum-legume intercropping. *J Agrometeorol.* 2020;24(2):156–62.
- American Oil Chemists' Society. Official methods and recommended practices of the AOCS. 5th ed. Champaign (IL): AOCS Press; 1993. Method Am 2-93.
- Soxhlet F. Die gewichtsanalytische Bestimmung des Milchfettes. *Dinglers Polytech J.* 1879;232:461–5.
- Behera UK, Rautaray SK. Effect of crop rotations on productivity and resource-use efficiency under rainfed lowlands. *Exp Agric.* 2010;46(2):195–216.
- Subbiah BV, Asija GL. A rapid procedure for estimation of available nitrogen in soils. *Curr Sci.* 1956;25:259–60.
- Bray RH, Kurtz LT. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.* 1945;59:39–45. <https://doi.org/10.1097/00010694-194501000-00006>
- Hanway JJ, Heidel H. Soil analysis methods used in Iowa State College Soil Testing Laboratory. *Iowa Agric.* 1952;57:1–31.
- Walkley A, Black IA. Examination of Degtjareff method for soil organic matter determination. *Soil Sci.* 1934;37:29–38. <https://doi.org/10.1097/00010694-193401000-00003>
- Jackson ML. Soil chemical analysis. Englewood Cliffs (NJ): Prentice Hall; 1973.
- Tabatabai MA, Bremner JM. Assay of urease activity in soils. *Soil Biol Biochem.* 1972;4(4):479–87. [https://doi.org/10.1016/0038-0717\(72\)90064-8](https://doi.org/10.1016/0038-0717(72)90064-8)
- Casida LE Jr, Klein DA, Santoro T. Soil dehydrogenase activity. *Soil Sci.* 1964;98(6):371–6. <https://doi.org/10.1097/00010694-196412000-00004>
- Ladd JN, Butler JHA. Short-term assays of soil proteolytic enzyme activities. *Soil Biol Biochem.* 1972;4(1):19–30. [https://doi.org/10.1016/0038-0717\(72\)90038-7](https://doi.org/10.1016/0038-0717(72)90038-7)

23. Singh RP, Verma SK, Meena R. Importance of sulfur in seed yield and oil content of toria. *Ann Agric Res.* 1997;18(4):452–7.
24. Chauhan A, Tripathi SC, Singh M. Phosphorus and sulfur influence on oil biosynthesis in *Brassica* crops. *J Agron Crop Sci.* 2002;188(3):159–64.
25. Hinsinger P. Bioavailability of phosphorus in acidic soils. *Plant Soil.* 2001;237(2):173–95. <https://doi.org/10.1023/A:1013351617532>
26. Bijarnia M, Meena RS, Singh J. Growth and yield response of toria to balanced fertilization. *Int J Plant Soil Sci.* 2017;15(3):1–8.
27. Shi Z, Zhang X, Li Y, Wang J, Xu M. Residual fertility effects of legume-cereal rotations under acid soils. *Field Crops Res.* 2024;302:109152.
28. Kumar S, Sharma P, Yadav R. Integrated nutrient management in toria for yield improvement. *J Oilseeds Res.* 2023;40(1):56–62.
29. Mohapatra P, Dixit A. Nutrient management for enhancing yield and oil quality of toria. *Indian J Agron.* 2010;55(2):127–32.
30. Gogoi B, Kalita B, Bhupenchandra I, Sutradhar P, Sharma KK. Soil carbon, microbial biomass carbon, soil health and productivity of *Brassica campestris* L. as affected by the application of organic manures. *J Environ Biol.* 2021;42(5):1379–86. <https://doi.org/10.22438/jeb/42/5/MRN-1648>
31. Ramírez L, Torres D, Fernández J. Organic carbon dynamics under diversified cropping. *Soil Tillage Res.* 2025;235:105756.
32. Adekiya AO, Ejue WS, Olayanju A, Dunsin O, Aboyeji CM, Aremu C, et al. Organic manure and NPK fertilizer effects on okra. *Sci Rep.* 2020;10(1):16083. <https://doi.org/10.1038/s41598-020-73291-x>
33. Amossé C, Jeuffroy MH, David C, Justes E. Cereal-legume intercropping improves nitrogen use efficiency. *Agron Sustain Dev.* 2021;41:63.
34. Li J, Wang Q, Zhang R, Chen Y. Soil enzyme activities under cereal-legume systems. *Appl Soil Ecol.* 2023;185:104718.
35. Nannipieri P, Trasar-Cepeda C, Dick RP. Soil enzyme activities as soil health indicators. In: Pankhurst C, Doube B, Gupta V, editors. *Biological indicators of soil health.* Wallingford (UK): CABI; 2012. p. 215–43.
36. Dick RP, Breakwell DP, Turco RF. Soil enzyme activities as microbiological indicators. In: Dick RP, editor. *Methods of soil enzymology.* Madison (WI): Soil Sci Soc Am; 2011. p. 256–73.
37. Bationo A, Ntare BR. Crop rotations and legume effects on soil fertility in tropical soils. *Nutr Cycl Agroecosyst.* 2000;57(1):1–15. <https://doi.org/10.1007/s10705-015-9700-y>
38. Akchaya K, Parasuraman P, Pandian K, Vijayakumar S, Thirukumaran K, Mustaffa MRAF, et al. Boosting resource use efficiency, soil fertility, food security, ecosystem services and climate resilience with legume intercropping: A review. *Front Sustain Food Syst.* 2025;9:1527256. <https://doi.org/10.3389/fsufs.2025.1527256>
39. Burns RG, DeForest JL, Marxsen J, Sinsabaugh RL, Stromberger ME, Wallenstein MD, et al. Soil enzymes in a changing environment. *Soil Biol Biochem.* 2013;58:216–34. <https://doi.org/10.1016/j.soilbio.2012.11.009>
40. Goudar K, Patil S, Naik R. Influence of crop rotations and organic amendments on soil fertility. *Indian J Agron.* 2017;62(4):525–31.
41. Peoples MB, Brockwell J, Hunt JR, Swan AD, Watson L, Hayes RC. Symbiotic nitrogen fixation in legumes. *Soil Biol Biochem.* 2019;146:107849.
42. Richardson AE, Barea JM, McNeill AM, Prigent-Combaret C. Acquisition of phosphorus and nitrogen in the rhizosphere. *Plant Soil.* 2009;321(1–2):305–39. <https://doi.org/10.1007/s11104-009-9895-2>
43. Aseri GK, Tarafdar JC. Leguminous residues and *Rhizobium* effects on soil enzymes. *Bioresour Technol.* 2006;97(3):330–5.
44. Bowles TM, Acosta-Martínez V, Calderón F, Jackson LE. Soil enzyme activities and microbial communities in organic systems. *Soil Biol Biochem.* 2014;68:252–62. <https://doi.org/10.1016/j.soilbio.2013.10.004>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.