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RECEIVED 16 January 2026

REVISED 06 March 2026

ACCEPTED 24 March 2026

PUBLISHED 16 April 2026

CITATION

Kishore AS, Sreelatha D, Reddy MM,
Nagesh Kumar MV and Kumar TS (2026)
Elucidating the carbon and nitrogen
pools with retention conservative
residues and fertility gradients on the
legume–maize system.
Front. Sustain. Food Syst. 10:1789677.
doi: 10.3389/fsufs.2026.1789677

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Elucidating the carbon and nitrogen pools with retention conservative residues and fertility gradients on the legume–maize system

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In light of the global climate scenario, this study addresses soil health, with emphasis on stabilizing carbon (C) and nitrogen (N) pools, highlighting the role of legumes as a cornerstone of cropping systems under conservation agriculture. The study evaluated the effects of N gradients and legume biomass incorporation on soil C and N pools in maize (*Zea mays* L.), variety DHM-121. The experiment was conducted for 2 years, that is, 2021–22 and 2022–23, in a semi-arid agroecosystem with varying N rates (100, 125, and 150% rate of N) in rabi maize, combined with the incorporation of legume biomass, *that is*, greengram (*Vigna radiata* L.) at 10 t ha⁻¹. Integrating 150% of N ha⁻¹ with legume biomass significantly increased soil organic C by 25% compared to 100% N, demonstrating potential for C-sequestration under NT. Soil microbial biomass N (SMBN) increased by 30%, and total soil N by 15%, underscoring the synergy between N gradients and legume biomass in enhancing soil fertility. Maize yield was highest in the combined treatment (150% of N ha⁻¹ + greengram biomass), averaging 6.8 t ha⁻¹, 18% higher than the control. Using 100% N on groundnut crops boosted soil penetration by 25% and aggregate stability by 20%, showing how biomass incorporation can strengthen soil structure for better maize growth. However, the combination of *legume biomass X N levels* and humus fraction was found to be non-significant. The research shows a novel combination that can be a game changer by integrating 150% N with greengram biomass, which markedly improved soil C, total N, and MBN, demonstrating enhanced soil fertility under no-till maize. The combined treatment also maximized maize yield, highlighting the synergistic effect of N gradients and legume residues. Additionally, legume biomass improved soil structure, indicating its role in sustaining productivity and soil health in semi-arid agroecosystems. The implications are deep for climate-smart agriculture that will deliver for future needs.

KEYWORDS

biomass carbon, humic acid, legume, penetration resistance, soil C:N, wetting pattern

Introduction

Maize (*Zea mays L.*) is a vital cereal crop that is an integral part of the food chain for food grains, nourishment, and forage. Renowned as the “Queen of Cereals” due to its versatility, it serves as a primary source of food for humans, a crucial component of animal feed, residues to the soil as a silage byproduct, and a key raw material for various agro-industries.

Globally, maize ranks third in cultivation area after wheat and rice, yet it leads in productivity, surpassing rice, wheat, and other millets. In India, maize is cultivated on 1.43 million hectares with 22.4 million tonnes of production, having an average productivity of 2,899 kg ha⁻¹, contributing to 9% of the national food basket, and emphasizing the significant role in the agricultural sector (Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, New Delhi, India, 2024).

Developmental variation over the century has been keystone with the balanced ecological biome with an approach of conservation agriculture. Agriculture, mainly focusing on the cropping system, has changed not only in terms of quantity but also quality, input to subjugate the climate change. To emphasize cropping systems, maize has been key for a large section of farmers in the world.

Improving crop yields through enhanced nutrient management is a key priority. The addition of legumes has proven highly effective, particularly with supplemental nitrogen (N) in achieving this goal. This approach not only boosts yield but also maintains soil health. Emphasizing nutrient enhancement and soil maintenance ensures sustainable agricultural practices (Rashid et al., 2022). The synergistic effect of legumes and N gradients was crucial in optimizing soil carbon (C) and N pools. Further, tillage has traditionally been integral to crop management, enhancing soil tilth, water retention, aeration, and moderating soil conditions (Virk et al., 2021; Karami et al., 2012).

The research findings confirmed that intensive tillage exacerbates soil compaction and reduces aggregate stability, ultimately disrupting soil productivity. It also decreases the retention and transport of water and solutes, while increasing losses due to runoff erosion (Phiri and Njira, 2023; Godard et al., 2008). Conversely, numerous benefits of no-till and minimum tillage have been documented, including enhanced porosity, organic C content, water-holding capacity, and reduced bulk density. Both practices improve aggregate stability, with zero tillage further reducing soil temperature and maintaining elevated C and N levels. These methods collectively contribute to better soil health and fertility (Irizar et al., 2013; Yadav et al., 2017).

Zero tillage in maize cultivation significantly reduces weed populations and lowers costs related to cultivation, irrigation, and nutrient requirements in legume-based cereal systems (Kimura and Uchida, 2020; Uzoma et al., 2021). The enhancement of soil fertility in cereal/legume systems is primarily associated with increased sequestration of soil organic C and turnover of nutrients (Abera and Gerkabo, 2021). Nutrient stoichiometry in soil–plant interactions plays a crucial role in regulating microbial metabolism and terrestrial nutrient limitations (Gong et al., 2021), with the potential limitation of ecosystem C sequestration ability by the balance of multiple elements (Tian et al., 2019). When stoichiometric imbalances lead to low C-use efficiency, more C will be directed toward detritus entering soils or sediments. Overyield of biomass in intercropping systems facilitates more C input to belowground, which is utilized for the formation of soil organic matter, predominantly driven by soil microbes (Xing et al., 2022; Wang et al., 2026).

Additionally, while legume residues and N levels enhance soil microbial activity and C content, the impact varies. Overall, these practices contribute to sustainable agricultural productivity (Beslemes et al., 2013). This potent addition also exerts a complementary influence on plant morphology and soil properties, resulting in enhanced efficiencies. The synergistic effects contribute to improved overall system performance, optimizing resource utilization and sustainability. This integration underscores the importance of holistic approaches in agricultural management (Omeke et al., 2021; Singh et al., 2015).

Further, nutrient stoichiometric imbalances in the cropping system can be mitigated through the integration of legumes, which help maintain ecological balance. In this context, the manuscript focuses on C and N dynamics in legume–maize cropping systems, emphasizing their role in soil–plant–atmospheric nutrient cycling and overall yield potential.

Materials and methods

Study area

The research experiment was carried out at 16°23'N latitude and 69°19'E longitude, with an altitude of 542.3 MSL. The site was located in semi-arid ecosystems during the autumn and spring of 2021–22 and 2022–23. The weather during the crop period was most congenial for the better performance of the legume–maize sequence. It falls under the Semi-Arid Tropics (SAT) according to Troll's classification, as depicted in Virmani et al., 1980. The weather parameters did not deviate much from the normal mean values of the location of study. The average temperature lies between 16.6 °C and 28.6 °C, with rainfall accounting for 885.23 mm, and sunshine hours range from 1.5 to 9 h day⁻¹.

Methodology

The research was framed with a split-plot design with legumes, such as groundnut, soybean, and greengram, with 100 and 75% nitrogen (N) rates as main plots for all three legumes in autumn, followed by 100, 125, and 150% N rates in spring, zero-till maize as subplots. The study was carried out over 2 years with three replications. Further, the inclusion of 125 and 150% of the recommended N rate in spring maize subplots was intended to evaluate crop response beyond the standard recommendation, identify optimum yield levels, and assess soil fertility and environmental implications. These rates allow a comprehensive assessment of N use efficiency under legume–maize cropping systems (Chen et al., 2018; Zhang et al., 2020).

The sowing for both years was taken up on 15 June for legumes and 15 Oct for spring maize. Need-based weed management was implemented using atrazine and paraquat during field preparation. For pest protection, particular attention was given to fall armyworm (*Spodoptera frugiperda*), and Emamectin benzoate 5 SG was applied according to the crop phenophases for maize (Tables 1, 2).

Soil penetration resistance (Milli pascals)

To measure soil penetration resistance, cone penetrometer values were taken within every experimental plot. Measurements were conducted at different depths, ranging from 15-cm intervals up to 30 cm.

TABLE 1 Soil properties in the experimental site.

S. No.	Particulars	Value
Physical properties		
1.	Mechanical analysis	
	Sand (%)	10.00
	Silt (%)	35.70
	Clay (%)	35.00
2.	Textural class	Sandy clay loam
3.	Bulk density (g cm ⁻³)	1.42
4.	Soil wetting pattern (%)	20.80
5.	Soil pH (1:2.5 soil: water suspension)	7.96
6.	Electrical conductivity (dS m ⁻¹)	0.42
7.	Organic C (%)	0.41
Chemical properties		
8.	Available N (kg ha ⁻¹)	249.8
9.	Available P ₂ O ₅ (kg ha ⁻¹)	35.5
10.	Available K ₂ O (kg ha ⁻¹)	374.6
11.	C:N ratio	9:1

The readings were obtained 2 days after irrigation to ensure consistency and exactitude when assessing the soil's resistance to penetration.

Soil aggregate stability

Soil aggregate stability was assessed using the wet sieving method. Air-dried soil aggregates (50 g) were pre-moistened and subjected to vertical oscillation in a sieve shaker for 30 min. Aggregates retained on each sieve were oven-dried and weighed after correcting for the coarse fraction. Water-stable aggregates (WSA > 0.25 mm) were expressed as a percentage of the initial sample weight, and mean weight diameter (MWD) was calculated to quantify aggregate stability and structural integrity. Further, following the methodology outlined by Black (1965).

Bulk density (g cc⁻¹)

The soil's bulk density at multiple depths was evaluated using the core sampler method. Soil samples were gathered from three site locations at varied depths after harvest. Soil samples were collected in triplicate at each depth and dried in a hot air oven at 105 °C for 48 h to estimate dry weight. The following formula was used to compute bulk density:

$$\text{Bulk density (g cc}^{-1}\text{)} = \frac{\text{Mass of soil oven dry weight basis (g)}}{\text{Core volume cm}^3}$$

Soil wetting pattern at 15-cm interval depths

Upon each irrigation period, soil samples were extracted using a screw auger from depths of 0–15 cm and 15–30 cm to quantify the

amount of wetness in the soil at that time. After extracting soil samples, they were placed in aluminium boxes and calibrated. The boxes were oven-dried to estimate the weight of soil samples. Using the equation presented by Black (1965), the available soil wetness was determined.

$$\text{Available soil moisture (\%)} = \frac{\text{Total moisture in the wet soil}}{\text{Oven-dried weight of total soil}} \times 100$$

$$\text{Gravimetric method} = \frac{W_1 - W_2}{W_2} \times 100$$

W₁- Weight of wet soil, W₂-Weight of dry soil.

Soil microbial biomass C (fumigation and extraction method)

Anderson and Domsch (1978) depicted the SMBC procedure by using the chloroform fumigation–extraction method. Moist sieved soil (20 g, triplicate) was adjusted to 55% water holding capacity. One set of samples was fumigated with alcohol-free chloroform (CHCl₃) under vacuum in a desiccator for 18–24 h at 25 °C, while the other set remained unfumigated as the control. After removing chloroform vapors, both fumigated and non-fumigated soils were extracted with 0.5 M K₂SO₄ (1:3.5 soil: extractant ratio) by shaking for 30 min and filtering. Organic C in the extracts was oxidized using K₂Cr₂O₇–H₂SO₄ digestion, diluted with distilled water, and back-titrated with 0.05 N ferrous ammonium sulfate using diphenylamine as indicator. SMBC was calculated from the difference between fumigated and non-fumigated extracts and expressed as µg C g⁻¹ soil.

$$\text{SMBC} = \frac{\text{C substrate in extract of fumigated soils} - \text{C substrate in extract of unfumigated soils}}{0.411 (\text{Kc})}$$

Soil microbial biomass nitrogen

Beck et al. (1997) stated the methodology for the SMBN as follows: Weigh five sets of 10 g soil samples. Place one set in a moisture box and weigh it to determine the moisture content. Take two of the remaining sets and place them in 50 mL beakers for fumigation. Pack the other two sets and keep them in the refrigerator for extraction the next day. After 24 h, transfer both fumigated and unfumigated soils into 250-ml conical flasks. Add 100 mL of 0.5 M K₂SO₄ to each flask and shake for 1 h. Filter the suspension through Whatman No.1 filter paper. Take 50 mL of soil extract from both fumigated and unfumigated samples. Digest these extracts for 3 h with a digestion mixture and 10 mL of sulfuric acid. After cooling, the total N content in the digested samples was measured and expressed as µg N g⁻¹ soil.

$$\text{SMBN} = \frac{\text{N content in extract of fumigated soils} - \text{N content in extract of unfumigated soils}}{0.57 (\text{K})}$$

TABLE 2 Recommended spacing and fertilizer application rates for various crop varieties.

Crop	Variety	Spacing (cm)	Fertilizer kg N-P ₂ O ₅ -K ₂ O ha ⁻¹	Duration (days)
Groundnut	K-8	30 * 10	20–40–50	100
Green gram	WGG-42	30 * 10	20–50–0	73
Soybean	JS-335	30 * 10	60–60–40	100
Spring Maize	DHM-121	60 * 20	240–80–80	120

Total carbon (%) in soil

To estimate total C, we used the loss on ignition method. One gram of soil sample was placed in a crucible that had been weighed beforehand. It was then dried in an oven at 105 °C for 6 h. After drying, the material was heated in a muffle furnace at 540 °C for 4 h. The sample was cooled to room temperature and then placed in a desiccator for 12 h. This process allowed us to determine the total C content of the soil.

$$\text{Total organic matter (\%)} = \frac{\text{Initial weight of sample} - \text{final weight of sample}}{\text{Weight of the sample taken}}$$

$$\text{Total C (\%)} = \frac{\text{Total organic matter}}{1.724}$$

Total nitrogen (%) in soil

To determine N content, we followed two main steps: digestion and distillation. Initially, one gram of the sample was digested with 10 mL of concentrated H₂SO₄ and 5 g of a catalyst mixture in a digestion unit. After digestion, the samples turned light green. Once cooled, the digestion tube was transferred to a distillation unit where N in the sample was converted into ammonium ions. The resulting distillate was then titrated with 0.02 N H₂SO₄ following the method outlined by Bremner and Mulvaney (1982).

$$\text{N content in the soil (\%)} = \frac{R (\text{titer value} - \text{blank value}) \times 0.1 \times 14 \times 100}{\text{Weight of the sample (0.5g)} \times 1000}$$

Determination of C:N ratio

To find-out the C:N values, fraction the C value by N content. The C/N ratio symbolizes the weight ratio of total C to N.

$$\text{C:N ratio} = \frac{\text{Total C content}}{\text{Total N content}}$$

Extraction of humus fractions

Tyurin's approach (Kononova, 2013) was used to identify and determine humic compounds, such as humic acid, humin, and fulvic acid, which were then extracted, fractionated, and purified from selected samples.

Statistical analysis

Using IBM SPSS Statistics 28.0, the data were statistically examined using the analysis of variance (ANOVA) technique, significant to the split block design (Gomez and Gomez, 1984). The F-test was utilized to ascertain the significance of the treatment effect, and the least significant differences (LSD) at the 5% probability level were employed to assess the treatment means. Using the R (doe-bioresearch) package, the PCA and correlation based on the test were carried out to compare the mean.

Results

Soil penetration resistance (M pa) and bulk density (g cm⁻³)

The experimental site's results, which are presented in Table 3, revealed significant variation at ($p = 0.05$) among the treatments, underscoring the fact that bulk density and resistance were higher in maize plots with groundnut sown prior (1.90 M pa, 1.47 g cm⁻³), and resistance was lower in soybean (1.75 M pa, 1.38 g cm⁻³) and green-gram production (1.67 M pa, 1.32 g cm⁻³). In terms of nitrogen (N) rates, 100% N exhibited stronger resistance (1.84 M pa) and bulk density (1.45 g cm⁻³) than 125 and 150% N.

Soil aggregates (> 0.25 mm) and soil wetting pattern at depths of 15 cm intervals

Soil wetting patterns at different layers (0–30 cm) and aggregate stability were most pronounced in the surface layers. This effect was greatest when autumn greengram biomass was combined with 100% N in spring maize, showing values of 21.94, 24.04, and 46.61%, compared to groundnut (12.63, 17.81, and 31.82%) and soybean (16.30, 21.57 and 37.76%).

Substantially considering N levels of spring maize, 150% N when applied maintained the soil wetting patterns (18.18, 22.53%), and soil clod firmness (41.40) was maintained with over 125% (17.13, 21.60, 39.48). Besides, 100% N exhibited the lower retention of soil wetting phenomena and clod firmness on surface and sub-surface levels (15.76, 20.47%, 36.71) in 2 years. Nevertheless, the association with residual retention versus N rates on maize was found to be negligible.

Soil microbial biomass (μ kg⁻¹ soil)

The variation in the soil microbial biomass activity is depicted in Tables 4, 5, which shows significantly higher response of the soil carbon (C) and nitrogen (N) microbial activity when the greengram biomass was retained on maize fields (23.20, 26.31, 99.47, and

TABLE 3 Soil physical properties of zero-till *spring* maize as influenced by *autumn* legumes and nitrogen fertility levels during 2021–22 and 2022–23.

Treatments	Resistance (M pa)			Aggregate stability (%)			Bulk density (g cc)			Soil wetness (0–15 cm)			Soil wetness (15–30 cm)		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
Autumn legumes x nitrogen levels (CXN)															
C1N1: Groundnut100% RDN	1.91	1.89	1.90	35.16	34.19	34.68	1.47	1.49	1.48	14.08	15.65	14.87	20.65	20.13	20.39
C1N2: Groundnut75% RDN	1.88	1.85	1.87	32.41	31.23	31.82	1.44	1.44	1.44	11.26	13.99	12.63	18.09	17.52	17.81
C2N1: Soybean100% RDN	1.82	1.82	1.82	41.03	40.26	40.65	1.41	1.40	1.41	17.43	17.70	17.57	22.52	22.11	22.32
C2N2: Soybean75% RDN	1.75	1.77	1.76	38.22	37.29	37.76	1.38	1.36	1.37	15.62	16.98	16.30	21.87	21.27	21.57
C3N1: Greengram100% RDN	1.71	1.69	1.70	47.01	46.21	46.61	1.35	1.32	1.34	22.14	21.73	21.94	24.76	23.72	24.24
C3N2: Greengram75% RDN	1.67	1.64	1.66	44.09	43.18	43.64	1.32	1.28	1.30	19.23	19.43	19.33	23.35	23.00	23.18
SEm±	0.02	0.01	-	0.32	0.40	-	0.01	0.01	-	0.46	0.11	-	0.15	0.18	-
C.D. (<i>p</i> = 0.05)	0.06	0.04	-	1.00	1.27	-	0.02	0.03	-	1.44	0.36	-	0.48	0.57	-
Spring maize with varied nitrogen fertility levels (F)															
F1: 100% RDN	1.85	1.83	1.84	37.17	36.24	36.71	1.46	1.44	1.45	15.94	15.57	15.76	20.74	20.20	20.47
F2: 125% RDN	1.80	1.78	1.79	39.86	39.09	39.48	1.43	1.41	1.42	17.39	16.86	17.13	21.82	21.38	21.60
F3: 150% RDN	1.73	1.72	1.73	41.93	40.86	41.40	1.40	1.39	1.40	18.55	17.81	18.18	22.76	22.30	22.53
SEm±	0.01	0.01	-	0.22	0.20	-	0.01	0.01	-	0.32	0.10	-	0.12	0.13	-
C.D. (<i>p</i> = 0.05)	0.03	0.03	-	0.65	0.60	-	0.02	0.02	-	0.94	0.29	-	0.35	0.39	-
Interaction															
Sub treatments at the same level as main treatments F X (C x N)															
SEm±	0.01	0.02	-	0.48	0.39	-	0.01	0.01	-	0.62	0.21	-	0.27	0.30	-
C.D. (<i>p</i> = 0.05)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at same/different levels of sub-treatments (C X N) X F															
SEm±	0.02	0.03	-	0.55	0.5	-	0.02	0.02	-	0.79	0.24	-	0.3	0.33	-
C.D. (<i>p</i> = 0.05)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-

RDN, recommended rate of nitrogen; WD, wetting patterns; BD, bulk density; DAS, days after sowing.

124.46 $\mu\text{C g}^{-1}$ soil) and (15.55, 25.88, 69.50, and 84.06 $\mu\text{N g}^{-1}$ soil), respectively, followed by groundnut and soybean at all the phenophase stages, that is, 15, 30, 45, and 60 days interval along with 100% N was superior to 75% N levels. Additionally, subplot treatments affirm that 50% more than normal N levels enhanced the microbial activity of C and N pools in surface and sub-surface layers, symbolizing the soil microfauna. On the other side, the interaction between the biomass retention of legumes and N levels was found to be frivolous.

The soil C:N ratio in the maize rhizosphere showed slight increases over the course of the experiment (Table 6). Across the 2-year study, soils under greengram (C3) residues consistently exhibited higher C:N ratios (12.5–13.9) compared to soybean (C2; 11.2–12.3) and groundnut (C1; 10.2–11.2) residues. Higher N rates applied to spring maize (125 and 150% of recommended N) slightly reduced soil C:N ratios compared to 100% N, reflecting enhanced N mineralization. Overall, legume residue quality and N fertilization influenced soil C:N, but the interactions between legume type and N rate were statistically non-significant, indicating a moderate effect of the treatments on soil organic matter stoichiometry during the short-term study.

Humus fractions at harvest of autumn and spring crops

The data outcomes from the four seasons of 2021–2023 illustrate that the impact of humus fraction (humic, fulvic acid, and humin) was not profound enough to be influenced by preceding legume residues on maize sequence with 0, 25, and 50% deviation from the recommended rates. As part of Table 7, the humic acid ranges from 1.01 to 1.31, the fulvic acid ranges from 0.41 to 0.60, and the humin ranges from 0.22 to 0.34, which are in positive linearity increase over the two years of study. Results were linear to Chen et al. (2018).

Grain yield

During 2021–22 and 2022–23, maize grown after kharif greengram residues with 100% RDN recorded significantly higher grain yields, 8–9% higher than 75% RDN greengram, 11–14% higher than 100% RDN soybean, and 17–20% higher than 75% RDN soybean. The lowest grain yields were observed with groundnut at 75% RDN (32–34% lower). Application of 150% RDN to rabi maize further increased yields, followed by 125% RDN, while 100% RDN resulted in the lowest yields. The combined treatment of maize following greengram with 100% RDN and 150% RDN in maize produced the highest grain yields (9,799 and 9,704 kg ha^{-1}), with 125% RDN being statistically comparable (9,386 and 9,276 kg ha^{-1}). The lowest yields were observed in maize, followed by groundnut at 75% RDN (6,148 and 6,001 kg ha^{-1}), as shown in Table 8.

Stover yield

Stover yields mirrored grain yield trends. Maize, after greengram residues, with 100% RDN produced higher stover than 75% RDN, followed by soybean and groundnut. Increasing N to 150% RDN significantly improved stover yield over 125 and 100% RDN. The interaction showed that maize after greengram with 100% RDN combined with 150% RDN in maize maximized stover production, though it was statistically comparable to 125% RDN. Greengram residues enhanced

dry matter accumulation, reflecting positive N $\times$ K synergy during vegetative and reproductive stages.

Discussion

Soil physical properties on maize sequence

Figure 1 shows PCA biplots for two consecutive years. In the first year, PC1 and PC2 explained 92.8 and 5.11% of the total variance, respectively, capturing 97.91% of the variability. Longer vectors for bulk density and soil moisture indicate their dominant contribution, while M30 and soil resistance, and BD and M15, show strong positive correlations. A similar eigenstructure and loading pattern in the second year confirmed the stability of relationships among BD, M15, M30, resistance, and aggregate stability across seasons. Similarly, in Figure 2, vector lengths and directions were comparable in 2 years, indicating stable associations among variables. In contrast, groundnut residues at higher rates, positioned farther from the origin, showed stronger associations with subsequent 18 treatments. Further similar trends are seen in Table 3.

The significant variation ($p \leq 0.05$) in bulk density and penetration resistance across treatments highlights the structural sensitivity of semi-arid soils to residue quality and N management. The comparatively higher BD and resistance in maize following groundnut may be linked to lower residue persistence and weaker aggregate-binding potential.

According to the aggregate hierarchy theory outlined by Yu et al. (2026), macroaggregates initially form around fresh organic residues and root materials and are subsequently stabilized into microaggregates over time. Greengram, due to its relatively labile biomass and favorable C:N ratio, likely promoted microbial proliferation and stimulated the production of extracellular polysaccharides and fungal hyphae, thereby enhancing macroaggregate formation and alleviating soil compaction. The reduced BD and resistance under greengram thus reflect improved pore connectivity and biopore formation driven by root growth and microbial binding agents.

N gradients influenced soil physical integrity via C–N coupling. Higher N (125–150%) enhanced biomass and root density, promoting soil loosening and aggregate stabilization. Increased N also stimulated rhizodeposition and microbial activity, forming organo–mineral complexes and glomalin, thereby improving structural stability and reducing resistance, as cited in Luo et al. (2020), Wang et al. (2021), and Zhou and Li, 2025.

Enhanced aggregate stability (>0.25 mm) and improved soil wetting patterns in surface layers (0–30 cm) reflect the concentration of organic inputs and active microbial turnover under no-till systems. The superior performance of autumn greengram biomass combined with 100% N suggests effective synchronization between biologically fixed N release and maize nutrient demand, and improving N further indicates that balanced nutrient supply enhances structural resilience through root-induced aggregation and microbial-mediated binding processes. However, the minimal interaction between residue retention and N rate suggests that residue quality and biological processes exert a more dominant influence on soil structural integrity than N rate alone in the semi-arid maize system. These study findings were in

TABLE 4 Microbial biomass C content ($\mu\text{g C g}^{-1}$ soil) of zero-till *spring* maize as influenced by *autumn* legumes and nitrogen fertility levels during 2021–22 and 2022–23.

Treatments	15 DAS			30 DAS			45 DAS			60 DAS		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
Autumn Legumes x nitrogen levels (CXN)												
C1N1: Groundnut100% RDN	13.21	14.09	13.65	30.90	33.93	32.42	77.80	79.71	78.76	107.14	109.39	108.27
C1N2: Groundnut75% RDN	10.65	11.67	11.16	26.38	28.44	27.41	72.01	73.62	72.82	99.88	102.46	101.17
C2N1: Soybean100% RDN	16.95	18.03	17.49	40.45	43.01	41.73	86.14	88.68	87.41	115.59	117.79	116.69
C2N2: Soybean75% RDN	15.12	16.22	15.67	37.20	39.52	38.36	80.87	84.58	82.73	112.50	113.92	113.21
C3N1: Greengram100% RDN	22.98	23.41	23.20	45.23	47.39	46.31	97.00	101.93	99.47	122.01	126.90	124.46
C3N2: Greengram75% RDN	19.02	20.57	19.80	43.50	45.31	44.41	92.34	94.42	93.38	118.97	122.10	120.54
SEm $\pm$	0.13	0.20	-	0.46	0.43	-	0.67	0.54	-	0.88	0.96	-
C.D. ($p = 0.05$)	0.39	0.62	-	1.45	1.34	-	2.10	1.71	-	2.78	3.03	-
Spring maize with varied nitrogen fertility levels (F)												
F1: 100% RDN	14.24	15.57	14.91	33.84	36.08	34.96	80.20	82.25	81.23	108.75	111.47	110.11
F2: 125% RDN	16.25	17.28	16.77	36.99	39.31	38.15	84.64	87.57	86.11	113.27	116.19	114.73
F3: 150% RDN	17.57	19.14	18.36	40.01	42.92	41.47	87.23	90.15	88.69	116.02	118.63	117.33
SEm $\pm$	0.11	0.16	-	0.22	0.26	-	0.51	0.55	-	0.78	0.69	-
C.D. ($p = 0.05$)	0.32	0.47	-	0.63	0.75	-	1.50	1.59	-	2.28	2.00	-
Interaction												
Sub treatments at the same level as main treatments F X (C x N)												
SEm $\pm$	0.23	0.31	-	0.47	0.58	-	1.21	1.29	-	1.79	1.52	-
C.D. ($p = 0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at the same/different levels of sub-treatments (C X N) X F												
SEm $\pm$	0.27	0.39	-	0.53	0.63	-	1.26	1.34	-	1.92	1.68	-
C.D. ($p = 0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-

TABLE 5 Microbial biomass N content ($\mu\text{g N g}^{-1}\text{soil}$) of zero-till *spring* maize as influenced by *autumn* legumes and nitrogen fertility levels during 2021–22 and 2022–23.

Treatments	15 DAS			30 DAS			45 DAS			60 DAS		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
Autumn Legumes x nitrogen levels (CXN)												
C1N1: Groundnut100% RDN	12.31	13.17	12.74	19.19	19.33	19.26	50.14	59.67	54.91	65.13	72.51	68.82
C1N2: Groundnut75% RDN	11.54	11.89	11.72	16.64	17.90	17.27	45.49	53.94	49.72	61.55	63.57	62.56
C2N1: Soybean100% RDN	13.74	14.50	14.12	22.31	23.01	22.66	58.46	67.99	63.23	74.12	78.28	76.20
C2N2: Soybean75% RDN	13.04	13.91	13.48	21.08	21.21	21.15	55.27	63.97	59.62	69.37	74.86	72.12
C3N1: Greengram100% RDN	15.21	15.88	15.55	25.03	26.73	25.88	65.98	73.02	69.50	82.15	85.96	84.06
C3N2: Greengram75% RDN	14.43	15.37	14.90	24.18	24.66	24.42	63.14	70.64	66.89	77.38	81.13	79.26
SEm $\pm$	0.20	0.16	-	0.18	0.51	-	0.81	0.47	-	0.59	0.85	-
C.D. ($p = 0.05$)	0.65	0.50	-	0.58	1.62	-	2.55	1.49	-	1.86	2.68	-
Spring maize with varied nitrogen fertility levels (F)												
F1: 100% RDN	13.12	13.81	13.47	17.80	20.31	19.06	54.69	58.70	56.70	67.47	71.03	69.25
F2: 125% RDN	13.91	14.57	14.24	21.34	22.75	22.05	59.94	63.99	61.97	72.46	76.87	74.67
F3: 150% RDN	14.42	14.93	14.68	23.78	24.58	24.18	62.78	66.93	64.86	74.92	80.25	77.59
SEm $\pm$	0.15	0.28	-	0.10	0.22	-	0.63	0.37	-	0.35	0.40	-
C.D. ($p = 0.05$)	0.45	0.28	-	0.30	0.64	-	1.83	1.07	-	1.02	1.17	-
Interaction												
Sub treatments at the same level as main treatments F X (C x N)												
SEm $\pm$	0.31	0.19	-	0.22	0.46	-	1.43	0.61	-	0.72	0.83	-
C.D. ($p = 0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at the same/different levels of sub-treatments (C X N) X F												
SEm $\pm$	0.38	0.23	-	0.25	0.54	-	1.54	0.90	-	0.86	0.98	-
C.D. ($p = 0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-

TABLE 6 C:N ratio of zero-till spring maize as influenced by autumn legumes and nitrogen fertility levels during 2021–22 and 2022–23.

Treatments	15 DAS			30 DAS			45 DAS			60 DAS		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
Autumn legumes x nitrogen levels (CXN)												
C1N1: Groundnut100% RDN	3.28	3.1	3.19	7.42	7.7	7.56	9.15	9.95	9.55	11.05	11.34	11.20
C1N2: Groundnut75% RDN	2.83	2.65	2.74	6.68	7.19	6.94	8.34	9.31	8.83	10.11	10.23	10.17
C2N1: Soybean100% RDN	4.10	3.81	3.96	8.66	8.74	8.70	10.42	10.76	10.59	13.03	13.25	13.14
C2N2: Soybean75% RDN	3.72	3.53	3.63	8.05	8.22	8.14	9.81	10.34	10.08	12.13	12.45	12.29
C3N1: Greengram100% RDN	4.89	4.37	4.63	9.92	9.73	9.83	11.79	11.72	11.76	14.55	14.67	14.61
C3N2: Greengram75% RDN	4.47	4.10	4.29	9.26	9.27	9.27	11.06	11.24	11.15	13.81	14.00	13.91
SEm±	0.11	0.08	-	0.19	0.10	-	0.20	0.11	-	0.22	0.19	-
C.D. ($p = 0.05$)	0.34	0.24	-	0.56	0.31	-	0.59	0.34	-	0.68	0.57	-
Spring maize with varied nitrogen fertility levels (F)												
F1: 100% RDN	3.57	3.46	3.52	8.01	7.85	7.93	10.62	10.39	10.51	13.40	13.16	13.28
F2: 125% RDN	3.86	3.70	3.78	8.32	8.18	8.25	11.16	10.96	11.06	13.99	13.75	13.87
F3: 150% RDN	4.15	3.99	4.07	8.62	8.43	8.53	11.52	11.27	11.40	14.42	14.23	14.33
SEm±	0.07	0.05	-	0.07	0.08	-	0.12	0.13	-	0.13	0.10	-
C.D. ($p = 0.05$)	0.20	0.14	-	0.21	0.23	-	0.33	0.37	-	0.38	0.28	-
Interaction												
Sub treatments at the same level as Main treatments F X (C X N)												
SEm±	0.13	0.11	-	0.16	0.18	-	0.21	0.26	-	0.28	0.21	-
C.D. ($p = 0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at same/different levels of sub-treatments (C X N) X F												
SEm±	0.17	0.12	-	0.18	0.20	-	0.29	0.31	-	0.32	0.24	-
C.D. ($p = 0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-

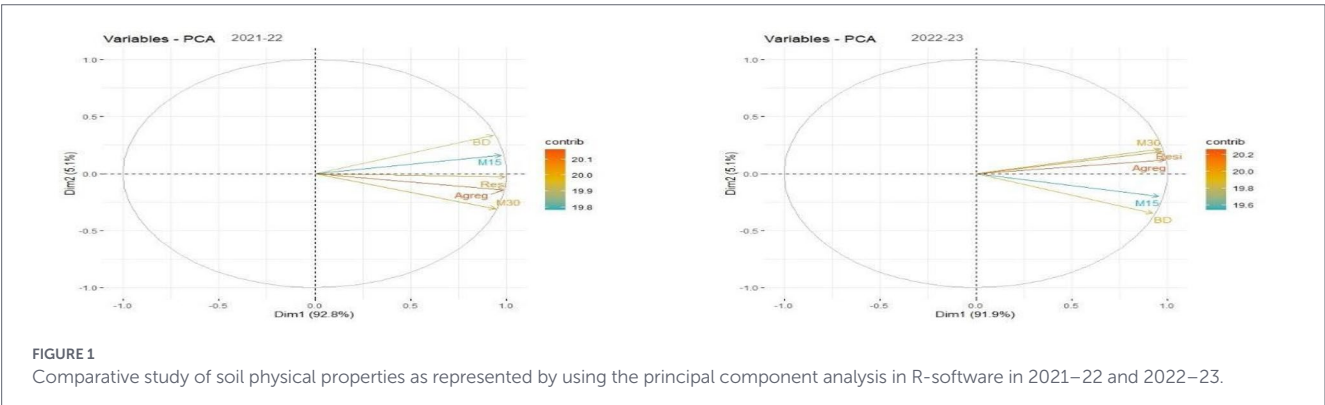
TABLE 7 Humus fractions at harvest of *spring* maize as influenced by *autumn* legumes and nitrogen fertility levels during 2021–22 and 2022–23.

Treatments	Humic acid			Fulvic acid			Humin		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
Autumn Legumes x nitrogen levels (CXN)									
C1N1: Groundnut100% RDN	0.95	1.12	1.04	0.4	0.52	0.46	0.22	0.23	0.23
C1N2: Groundnut75% RDN	0.94	1.08	1.01	0.37	0.44	0.41	0.22	0.22	0.22
C2N1: Soybean100% RDN	1.41	1.2	1.31	0.46	0.64	0.55	0.32	0.32	0.32
C2N2: Soybean75% RDN	1.32	1.18	1.25	0.43	0.54	0.49	0.25	0.25	0.25
C3N1: Greengram100% RDN	1.15	1.22	1.19	0.55	0.65	0.60	0.33	0.34	0.34
C3N2: Greengram75% RDN	1.14	1.21	1.18	0.53	0.64	0.59	0.33	0.33	0.33
SEm±	0.08	0.10	-	0.02	0.02	-	0.03	0.03	-
C.D. (<i>p</i> = 0.05)	NS	NS	-	NS	NS	-	NS	NS	-
Spring maize with varied nitrogen fertility levels (F)									
F1: 100% RDN	1.10	1.14	1.12	0.44	0.55	0.50	0.26	0.27	0.27
F2: 125% RDN	1.15	1.17	1.16	0.46	0.57	0.52	0.27	0.28	0.28
F3: 150% RDN	1.19	1.19	1.19	0.47	0.60	0.54	0.30	0.30	0.30
SEm±	0.07	0.08	-	0.01	0.01	-	0.01	0.01	-
C.D. (<i>p</i> = 0.05)	NS	NS	-	NS	NS	-	NS	NS	-
Interaction									
Sub treatment at the same level as main treatments F X (C X N)									
SEm±	0.15	0.16	-	0.02	0.02	-	0.03	0.04	-
C.D. (<i>p</i> = 0.05)	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at the same/different levels of sub-treatments (C X N) X F									
SEm±	0.18	0.19	-	0.02	0.02	-	0.04	0.05	-
C.D. (<i>p</i> = 0.05)	NS	NS	-	NS	NS	-	NS	NS	-

TABLE 8 Grain and straw yield (kg ha⁻¹) of zero-till *rabi* maize as influenced by *kharif* legumes and nitrogen fertility levels during 2021–22 and 2022–23.

Treatments	Grain yield (kg ha ⁻¹)			Straw yield (kg ha ⁻¹)		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean
Kharif legumes x nitrogen levels (CXN)						
C ₁ N ₁ : Groundnut _{100%} RDN	7,957	7,755	7,856	9,851	9,661	9,756
C ₁ N ₂ : Groundnut _{75%} RDN	6,963	6,804	6,884	8,707	8,486	8,596
C ₂ N ₁ : Soybean _{100%} RDN	8,073	8,192	8,299	10,337	10,196	10,267
C ₂ N ₂ : Soybean _{75%} RDN	7,798	7,622	7,710	9,630	9,451	9,541
C ₃ N ₁ : Greengram _{100%} RDN	9,193	9,089	9,141	11,250	11,073	11,173
C ₃ N ₂ : Greengram _{75%} RDN	8,480	8,302	8,391	10,383	10,305	10,377
SEm±	61	35	-	59	57	-
C.D. (<i>p</i> = 0.05)	191	102	-	192	180	-
Rabi maize with varied nitrogen fertility levels (F)						
F ₁ : 100% RDN	7,407	7,229	7,318	9,207	9,012	9,110
F ₂ : 125% RDN	8,059	8,054	8,140	10,116	9,974	10,067
F ₃ : 150% RDN	8,766	8,599	8,682	10,756	10,599	10,678
SEm±	39	35	-	32	43	-
C.D. (<i>p</i> = 0.05)	112	101	-	94	124	-
Interaction						
Sub treatments at the same level of main treatments F X (C x N)						
SEm±	168	156	-	159	172	-
C.D. (<i>p</i> = 0.05)	486	451	-	462	498	-
Main treatments at the same/different level of sub treatments (C X N) X F						
SEm±	153	143	-	142	160	-
C.D. (<i>p</i> = 0.05)	475	430	-	430	480	-

RDN, Quantity of N, P₂O₅, and K₂O used.



concurrence with those of Hazra et al. (2019), Talukder et al. (2022), Chichongue et al. (2020), Liben et al. (2018), and Singh et al. (2015). Meena et al. (2015) made a comparable observation, which is noticed in Figures 3–6.

Soil biological properties on zero-till maize

Figure 7 revealed strong positive correlations between microbial C and N across soil layers, often exceeding 0.70 and highly significant (**), particularly influenced by early greengram residue retention in maize. Correlations such as BC15.das versus BC30.das (0.78–0.82)

and BC30.das versus BC45.das (0.77–0.90 ***) indicate that microbial activity intensifies from 15 to 60 days after sowing, peaking as residue decomposition progresses. Moderate negative correlations at later stages highlight shifts in N availability as biomass is consumed. These results demonstrate that sustained residue retention enhances microbial activity and soil nutrient cycling more effectively than split N application alone. Alike, trends pertaining to SMBC and SMBN are seen in Tables 4, 5.

Figure 8 illustrates the direction and strength of associations between microbial biomass C and N, with circle size and color representing intensity and correlation sign-blue for positive and red for

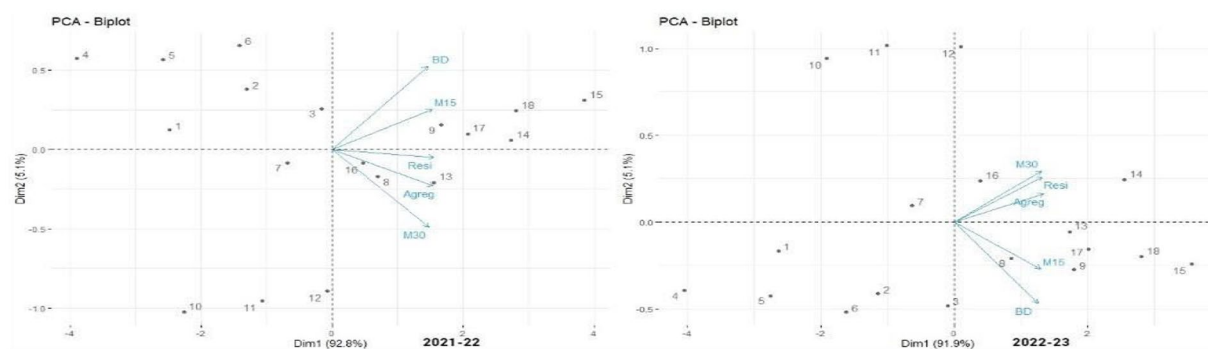


FIGURE 2

Relative study of treatment combinations (legume residues X nitrogen levels) of soil physical properties as represented by using principal component analysis in R-software in 2021–22 and 2022–23. BD, bulk density; Agreg, aggregate stability; BN, biomass nitrogen; BC, biomass carbon. M15 and M30 for soil moisture at 0–15 cm and 15–30 cm.



FIGURE 3

Zero-till maize at tasseling stage grown after green gram at 100–125% RDN in autumn and spring seasons.



FIGURE 4

Zero-till maize at tasseling stage grown after green gram at 100–150% RDN in the autumn and spring seasons.

negative. Further, showing strong positive correlations between microbial biomass C and N, with large blue circles indicating consistent associations across 2 years. Greengram residues, owing to their low C:N ratio, accelerated decomposition and nutrient mobilization, enhancing microbial activity and soil microfauna compared to

soybean and groundnut. Lower N in autumn reduced residue production, which was reflected in diminished soil activity in spring maize. Overall, greengram biomass maintained superior synchrony between microbial C and N from 15 to 60 days after sowing, highlighting the critical role of residue retention in soil nutrient cycling.



FIGURE 5
Zero-till maize at the cob stage grown after greengram at 100–125% RDN in the autumn and spring seasons.



FIGURE 6
Zero-till maize at the cob stage grown after greengram at 100–150% RDN in the autumn and spring seasons.

Greengram residue retention significantly increased soil microbial biomass C ($23.20\text{--}124.46\ \mu\text{g C g}^{-1}$) and N ($15.55\text{--}84.06\ \mu\text{g N g}^{-1}$) by accelerating decomposition through its low C:N ratio, providing labile nutrients for microbes. Groundnut and soybean also enhanced microbial biomass, but to a lesser extent due to slower residue turnover. Higher N levels (100–150%) further stimulated microbial activity via increased root growth and rhizodeposition, while the negligible interaction with residue type suggests that residue quality predominantly drives microbial biomass.

Collectively, these findings support the C–N coupling theory in Wu et al., 2025, whereby synchronized C and N availability from quality residues drives microbial biomass and nutrient cycling in semi-arid maize systems under conservation agriculture. These results align with Yusuf et al. (2009), Kumar et al. (2018), Xing et al. (2022), and Gregorich et al. (2001), with comparable trends shown by Banda et al. (2018) and Lalonde et al. (2004) (Figures 9, 10). Higher N rates enhanced biomass N and microbial activity, while lower rates had reduced effects. Similar patterns were reported by Zuber et al. (2018).

Soil C:N ratio is a key indicator of organic matter quality and nitrogen availability. In this study, soils under greengram residues showed higher C:N ratios, which may be attributed to the relatively higher carbon content and slower decomposition of greengram biomass compared to groundnut and soybean. Increasing N rates in maize slightly reduced soil C:N ratio, likely due to accelerated

microbial decomposition and mineralization of organic residues, which increased soil N relative to C. These findings are consistent with previous studies showing that legume residues with higher C:N ratios can gradually enhance soil organic matter and influence N cycling (de Jesus et al., 2025; Liu et al., 2024). The non-significant interactions between legume type and N rate suggest that, within the short experimental period, soil C:N responds primarily to residue quality rather than the combination of residue and N rate. Longer-term studies are expected to show more pronounced effects on soil C:N dynamics under legume-maize rotations.

The humus fraction over the four seasons (2021–2023) showed that humic acid ranged from 1.01 to 1.31, fulvic acid from 0.41 to 0.60, and humin from 0.22 to 0.34. Although these changes were not statistically significant, all humus fractions exhibited a consistent positive trend over the two-year experimental period. This indicates a gradual increase in soil organic C fractions under maize following legume residues, even with 0, 25, and 50% deviations from recommended N rates. The observed linear trends align with Chen et al. (2018), who reported that humus fractions in short-term experiments often show subtle changes that become more pronounced over longer durations. Therefore, while the current study reflects early-stage responses, these data provide valuable baseline information for understanding the potential cumulative effects of legume residues on soil organic matter in longer-term legume-maize cropping systems.



The yield parameters were consistent with the values reported in Table 8. The higher grain and stover yields under greengram residue retention and elevated N levels can be attributed to improvements in both biological and physical soil properties. Enhanced SMBC (23.20–124.46 $\mu\text{g C g}^{-1}$) and N (15.55–84.06 $\mu\text{g N g}^{-1}$) accelerated residue

The low C:N ratio of greengram residues further enhanced microbial efficiency and rapid nutrient release, promoting better



FIGURE 10
Maize cobs at 100–150% RDN in the autumn and spring seasons.

synchronization between nutrient availability and crop demand. Collectively, these biological and physical improvements synergistically enhanced nutrient uptake, biomass accumulation, and ultimately grain and stover yields, demonstrating the critical role of residue quality and soil health management in zero-till maize systems. Further, corroborating findings of Shukla et al. (2025).

Conclusion

Greengram residue retention with 100–150% N markedly improved soil microbial biomass ($23.20\text{--}124.46\ \mu\text{g C g}^{-1}$; $15.55\text{--}84.06\ \mu\text{g N g}^{-1}$), aggregate stability (46.61%), and reduced bulk density ($1.32\ \text{g cm}^{-3}$) and resistance (1.67 MPa) in maize. These effects were driven by low C:N ratio of greengram residues, which accelerated decomposition, stimulated microbial proliferation, and promoted C–N coupling, thereby enhancing soil structural integrity and nutrient cycling. Minimal interaction between residue type and N indicates that residue quality is the dominant driver of soil health in the semi-arid maize system.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AK: Data curation, Writing – original draft, Formal analysis, Writing – review & editing, Investigation. DS: Writing – review & editing, Writing – original draft, Methodology, Supervision, Project

administration, Conceptualization. MR: Formal analysis, Resources, Project administration, Writing – original draft, Conceptualization, Supervision, Writing – review & editing. MN: Project administration, Writing – original draft, Visualization, Validation, Resources, Supervision, Writing – review & editing. TK: Funding acquisition, Writing – review & editing, Writing – original draft, Supervision, Resources, Software, Project administration, Visualization, Validation.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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