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Dynamics of carbon-to-nitrogen (C:N) ratio during bio-conservation of diverse crop residues as influenced by microbial decomposer inoculants

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ABSTRACT

This study aimed to evaluate the performance of selected microbial decomposer inoculations on the Carbon-to-Nitrogen (C:N) ratio dynamics of diverse crop residues. Using a Factorial Randomized Block Design, four residues—paddy straw, sesame stalks, redgram stalks, and cotton stubbles—were treated with two distinct microbial consortia (Decomposer-1 and Decomposer-2) and a control group over a 120-day composting period. Results showed a significant progressive decline in the C:N ratio across all treatments, with Decomposer-1 (comprising *Trichoderma reesei*, Xyline-degrading bacteria, PSB, and ZSB) exhibiting the highest efficiency. Decomposer-1 reduced the mean C:N ratio to 26.02, achieving the stability threshold of less than 30:1 within 60 to 80 days, whereas the control required 110 days or more. The study concludes that microbial-assisted bio-conservation effectively transforms recalcitrant waste into stable, nutrient-dense organic manure, providing a sustainable alternative to open-field residue burning.

Keywords: C:N ratio, Microbial decomposer, Crop residues, Aerobic composting, Bio-conservation

Introduction

The maintenance and preservation of soil health are universally regarded as the primary responsibilities for ensuring long-term, sustainable agricultural productivity and global food security. Soil is a finite, living resource, yet modern intensive cultivation practices—predominantly characterized by a heavy reliance on high-analysis chemical fertilizers and synthetic pesticides—have led to a gradual but steady deterioration of soil fertility, organic matter content, and biological health (Mandal, Misra, Hati, Bandyopadhyay, Ghosh and Mohanty, 2004 [1]; Meena, Kumar, Datta, Lal, Vijayakumar, Jhariya and Pathak, 2020) [2]. A significant and escalating challenge in contemporary agriculture is the effective management of massive quantities of crop residues. India, being an agrarian powerhouse, generates approximately 500 million tonnes of crop residues annually (NPMCR, 2014; Bhuvaneshwari *et al.*, 2019) [4, 3].

In the specific agro-climatic context of the Northern Telangana Zone, residues from prominent crops such as paddy (*Oryza sativa*), cotton (*Gossypium hirsutum*), sesame (*Sesamum indicum*), and redgram (*Cajanus cajan*) represent a major biomass surplus. While a fraction of this lignocellulosic material is utilized for animal feed, domestic fuel, or industrial purposes, a staggering 92 million tonnes are disposed of through open-field burning annually across the nation (Bhuvaneshwari, Hettiarachchi and Meegoda, 2019; Dube, 2022) [3]. This practice is environmentally disastrous, as the combustion of agricultural residues leads to the emission of harmful radiative gases, particulate matter (PM2.5 and PM10), and chemical pollutants that severely degrade air quality and threaten human health. From an agronomic standpoint, burning results in the near-total loss of organic carbon (100%) and substantial depletion of essential nutrients, including approximately 80% of nitrogen, 25% of phosphorus, 21% of potassium, and 50–60% of sulphur (Mandal, Misra, Hati, Bandyopadhyay, Ghosh and Mohanty, 2004 [1]; Bhuvaneshwari, Hettiarachchi and Meegoda, 2019; Dube, 2022) [5].

The primary physiological and biochemical bottleneck preventing the rapid soil incorporation or natural decomposition of these residues is their inherently wide Carbon-to-Nitrogen (C:N) ratio. For instance, cereal residues like paddy straw often exhibit an initial C:N ratio as high as 71.9:1, which significantly surpasses the ideal range of 30:1 to 35:1 required for efficient microbial metabolism and stabilization (Viji *et al.*, 2015) [6]. When such high-carbon residues are added to the soil without prior decomposition, they trigger a microbial "nitrogen grab," leading to temporary nitrogen immobilization. This phenomenon deprives the standing or succeeding crop of available nitrogen, resulting in stunted growth, chlorosis, and significant yield penalties (Gaiind *et al.*, 2007; Meena *et al.*, 2020) [7, 2].

Biological recycling through aerobic composting offers a sustainable, eco-friendly alternative to burning. This complex biochemical process is driven by diverse populations of microorganisms that secrete extracellular enzymes—specifically cellulases, hemicellulases, and ligninases—to break down complex polymeric structures like cellulose, hemicellulose, and lignin into simpler organic forms and stable humus (Kumar *et*

al., 2020) [8]. The rate and efficiency of this transformation are heavily influenced by the presence and activity of potent microbial decomposer inoculants. Recent biotechnological advancements have demonstrated that specialized microbial consortia can significantly accelerate the narrowing of the C:N ratio, transforming recalcitrant waste into nutrient-rich, stable compost within a much shorter duration than traditional methods (Bhattacharjya, Sahoo, Doppa, Hopewell, Srivastva, Das and Sharma, 2021 [9]; Sood, Sharma, Kumar, Bamboriya, Shrivastava and Mazumdar, 2022) [10]. Furthermore, the efficacy of decomposition is often a reflection of the substrate's biochemical complexity. Residues like cotton stubbles and redgram stalks contain higher concentrations of lignin compared to paddy straw, requiring more robust enzymatic intervention (Viji et al., 2015) [6]. Given this context, the present investigation was undertaken to evaluate the performance of selected microbial decomposer inoculations on the C:N ratio dynamics of diverse crop residues. The study aims to provide a viable, rapid bio-conservation technology that empowers farmers to manage residues effectively, thereby promoting soil health and environmental sustainability.

Materials and Methods

The experimental investigation was conducted during the *Kharif* season of 2019 at the Agricultural College Farm, Jagtial, situated in the Northern Telangana Zone of India. The research site is geographically positioned at 18°49' 40.2" N latitude and 78°54' 49.6" E longitude, with an elevation of 243.4 meters above mean sea level. The region is characterized by a semi-arid climate, and the study was executed under controlled composting conditions to ensure scientific accuracy (Viel et al., 1987) [11]. The experiment was laid out in a Factorial Randomized Block Design (FRBD) with three replications, comprising twelve treatment combinations consisting of four crop residues and three microbial decomposer levels.

2.1. Selection and characterization of crop residues

Four predominant crop residues representing various biochemical complexities were selected for the study: Paddy straw (*Oryza sativa*), Sesame stalks (*Sesamum indicum*), Redgram stalks (*Cajanus cajan*), and Cotton stubbles (*Gossypium hirsutum*). These residues were collected post-harvest, sun-dried to a constant weight, and mechanically shredded into smaller fragments of 5–10 cm. This pre-treatment was essential to increase the specific surface area available for microbial attachment and to disrupt the recalcitrant lignocellulosic matrix, thereby enhancing the penetrability of extracellular enzymes (Viji et al., 2015; Shrivastava et al., 2018) [6, 12].

2.2. Microbial inoculants and consortium composition

The study evaluated two distinct microbial consortia specifically formulated for high lignocellulolytic activity against a control group. The treatment details are as follows:

- **Treatment 1 (D1 - Control):** Natural composting facilitated by indigenous microflora without the addition of external inoculants.
- **Treatment 2 (D2 - Decomposer-1):** Application of a specialized consortium comprising *Trichoderma reesi*, Xyline-degrading bacteria, Phosphorus Solubilizing Bacteria (PSB), and Zinc Solubilizing Bacteria (ZSB). This consortium was designed to address both structural degradation and nutrient mineralization (Gaur, 1982; Shrivastava et al., 2018) [13, 12].
- **Treatment 3 (D3 - Decomposer-2):** Application of a fungal-dominant consortium consisting of *Aspergillus nidulans*, *Trichoderma viridae*, and *Phaenerochete chrysogenum*. These species are recognized for their robust lignin-peroxidase and cellulase production (Tripathi et al., 1991; Kumar et al., 2020) [14, 8].

2.3. Composting procedure and environmental management

Composting was carried out using the heap method, with each heap consisting of 10 kg of shredded residue. The microbial consortia were applied as a liquid formulation at a rate of 200 liters of solution per ton of residue to ensure uniform distribution. Moisture levels were strictly maintained within the optimal range of 55–60% of the water-holding capacity through periodic sprinkling of water. To facilitate aerobic conditions and prevent the development of anaerobic pockets, manual turning of the heaps was performed at 7-day intervals (Viel et al., 1987) [11]. The composting process was monitored for a total duration of 120 days.

2.4. Sampling and laboratory analysis

Representative composite samples were collected from each heap at 10-day intervals (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 days). The samples were air-dried, ground, and passed through a 2-mm sieve for chemical analysis.

- **Total Organic Carbon (TOC):** Estimated using the dry ash method by igniting the samples in a muffle furnace at 550 °C for 6 hours. This method ensures the complete oxidation of organic matter to CO₂, allowing for an accurate calculation of the remaining carbon skeleton (Tiquia et al., 2000) [15].
- **Total Nitrogen (N):** Determined by the modified Kjeldahl method, involving digestion with concentrated H₂SO₄ followed by distillation with 40% NaOH into a boric acid indicator solution (Bremner, 1965) [16].
- **C:N Ratio:** Calculated as the mathematical quotient of the Total Organic Carbon and Total Nitrogen values obtained at each sampling stage.

2.5. Statistical analysis

The data were subjected to statistical analysis of variance (ANOVA) for a Factorial Randomized Block Design. The significance of the treatment effects was determined using the *F*-test, and the Critical Difference (CD) at a 5% probability level was calculated to compare treatment means (Gomez et al., 1984) [17].

Results and Discussion

3.1. Dynamics of C:N ratio during the composting process

The Carbon-to-Nitrogen (C:N) ratio is widely recognized as one of the most critical parameters for assessing the maturity, stability, and agricultural suitability of compost. It serves as a biochemical proxy for the degree of organic matter humification (Senesi, 1989; Tiquia et al., 2000) [18, 15]. In the present investigation, a significant and progressive decline in the C:N ratio was observed across all crop residues and microbial treatments from the initial day to the 120th day of composting (Table 4.3).

At the commencement of the study (Day 0), the C:N ratio varied significantly depending on the residue type. Paddy straw (S1) recorded the widest initial C:N ratio (71.94), followed by cotton stubbles (S4) at 48.37, redgram stalks (S3) at 40.26, and sesame stalks (S2) at 38.75. These inherent differences are strictly attributed to the initial chemical composition, specifically the varying concentrations of recalcitrant structural polymers like cellulose and lignin, and the baseline nitrogen content of the specific plant tissues (Viji and Neelanarayanan, 2015 [6]; Bhattacharjya, Sahoo, Doppa, Hopewell, Srivastva, Das and Sharma, 2021) [9].

3.2. Comparative efficacy of microbial decomposers

The application of exogenous microbial consortia significantly accelerated the reduction of the C:N ratio compared to the control group (D1), which relied solely on indigenous microflora (*P* < 0.05). Among the evaluated treatments, **Decomposer-1 (D2)** consistently exhibited the highest efficiency in narrowing the C:N ratio across all sampling intervals.

By the end of the 120-day composting period, the mean C:N ratio across all residues under the D2 treatment was reduced to 26.02,

whereas the control (*D1*) remained significantly higher at 32.20. Specifically, in the case of the highly recalcitrant paddy straw (*S1*), the treatment with *D2* resulted in a final C:N ratio of 20.09, which is a marked improvement over the 32.00 recorded in the control group. The superior performance of Decomposer-1 is likely due to the synergistic interaction between *Trichoderma reesi* (a potent cellulase producer) and Xyline-degrading bacteria, which effectively break down the hemicellulose-cellulose-lignin complex (Kumar *et al.*, 2020; Sood *et al.*, 2022) [8, 10].

3.3. Achievement of compost maturity and stability

Compost is considered "mature" and safe for soil application when the C:N ratio falls below the threshold of 30:1. Ratios above this level can lead to biological nitrogen immobilization, causing nitrogen deficiency in crops (Gaind *et al.*, 2007; Meena *et al.*, 2020) [7, 2].

In this study, the time required to reach this stability milestone varied by treatment:

- **Paddy Straw (S1):** Under the influence of Decomposer-1 (*D2*), the ratio dropped to a stable 27.98 by **Day 80**, whereas the control took 110 days to cross the 30:1 mark.
- **Sesame Stalks (S2):** Reached a stable ratio earlier, crossing the threshold by **Day 90** under the *D2* treatment.
- **Redgram (S3) and Cotton (S4):** Both residues achieved maturity between **Day 90 and 100** when treated with microbial inoculants.

The rapid narrowing of the C:N ratio is primarily a result of two simultaneous biological processes: the mineralization of organic carbon into CO₂ through microbial respiration (carbon loss) and the concentration of nitrogen as the total biomass weight decreases due to decomposition (Tiquia *et al.*, 2000; Bhattacharjya *et al.*, 2021) [15, 9].

This logic is further supported by the high **Dehydrogenase activity**—a marker of total microbial metabolic flux—recorded during the initial thermophilic and mesophilic phases of the process (Sood *et al.*, 2022) [10].

Conclusion

The results of the present investigation conclusively demonstrate that the application of exogenous microbial consortia is a highly effective strategy for the rapid bio-decomposition of recalcitrant agricultural residues. Among the four residues evaluated, paddy straw posed the most significant biochemical challenge due to its exceptionally wide initial C:N ratio (71.94), whereas sesame stalks, with a narrower initial ratio, were decomposed more readily.

The research identifies **Decomposer-1 (D2)**—a strategic consortium of *Trichoderma reesi*, Xyline-degrading bacteria, and nutrient-solubilizing bacteria—as the most proficient treatment for accelerating the composting process. This treatment successfully narrowed the C:N ratio to the stable maturity threshold of less than 30:1 within **60 to 80 days**, depending on the residue type. This represents a substantial temporal advantage over the control group, which required 110 days or more to achieve similar stability milestones.

The rapid reduction in the C:N ratio, driven by intense cellulolytic and lignolytic enzymatic activity, ensures that the final compost is biologically stable and chemically balanced. By converting high-carbon waste into low-carbon, nutrient-dense organic manure, this technology mitigates the risk of soil nitrogen immobilization that occurs with the direct incorporation of raw residues. Consequently, the adoption of microbial-assisted bio-conservation serves as a technically viable and environmentally sustainable alternative to the hazardous practice of open-field residue burning, facilitating enhanced soil health and circular nutrient management in the Northern Telangana Zone.

Table 1. Effect of crop residues and decomposers on C:N ratio during composting

Crop Residues	Period of composting (days)												
	0	10	20	30	40	50	60	70	80	90	100	110	120
S ₁	71.94	68.61	64.81	57.42	53.80	47.07	42.00	38.07	36.03	33.39	30.36	26.15	24.90
S ₂	38.75	38.13	37.60	36.43	35.40	34.83	33.93	33.43	32.83	31.77	31.00	30.17	29.53
S ₃	40.26	40.00	39.37	38.80	38.23	36.17	35.67	35.23	34.77	33.70	31.97	31.47	30.90
S ₄	48.37	47.07	45.70	44.50	43.73	42.27	41.37	40.07	38.57	34.83	33.80	32.23	30.00
SEm±	0.67	0.64	0.61	0.59	0.61	0.58	0.50	0.48	0.45	0.44	0.44	0.42	0.37
CD(P = 0.05)	1.97	1.88	1.79	1.74	1.79	1.70	1.47	1.40	1.31	1.28	1.30	1.23	1.08
Decomposer													
D ₁	49.83	49.06	48.20	47.30	46.14	44.62	41.21	40.20	39.26	37.65	36.29	33.34	32.20
D ₂	49.83	48.01	45.81	40.34	39.38	35.99	35.33	34.18	32.94	29.66	28.09	26.89	26.02
D ₃	49.83	48.28	46.60	45.22	42.86	39.64	38.18	35.72	34.45	32.95	30.96	29.78	28.28
SEm±	0.58	0.56	0.53	0.51	0.53	0.50	0.43	0.41	0.39	0.38	0.38	0.36	0.32
CD(P = 0.05)	NS	NS	1.56	1.51	1.55	1.47	1.27	1.21	1.13	1.11	1.13	1.06	0.94
Interactions													
S ₁ D ₁	71.94	69.85	68.41	66.91	64.37	62.07	52.05	50.12	48.82	45.52	42.47	32.98	32.00
S ₁ D ₂	71.94	67.86	62.22	45.06	42.72	34.27	33.11	30.92	27.98	25.94	23.76	21.56	20.09
S ₁ D ₃	71.94	68.12	63.80	60.28	54.32	44.88	40.83	33.17	31.28	28.71	24.85	23.92	22.62
S ₂ D ₁	38.75	38.50	38.09	37.60	36.90	36.10	34.30	33.70	33.40	33.00	32.80	32.60	32.00
S ₂ D ₂	38.75	37.80	37.10	34.60	34.10	33.60	33.00	32.50	32.20	29.70	29.40	28.00	27.40
S ₂ D ₃	38.75	38.10	37.60	37.10	35.20	34.80	34.50	34.10	32.90	32.60	30.80	29.90	29.20
S ₃ D ₁	40.26	40.10	39.60	39.10	38.60	37.70	36.80	36.30	35.90	34.60	33.70	33.30	32.50
S ₃ D ₂	40.26	39.90	39.10	38.50	37.90	34.40	34.10	33.80	33.30	33.00	29.60	29.40	28.70
S ₃ D ₃	40.26	40.00	39.40	38.80	38.20	36.40	36.10	35.60	35.10	33.50	32.60	31.70	31.50
S ₄ D ₁	48.37	47.80	46.70	45.60	44.70	42.60	41.70	40.70	38.90	37.50	36.20	34.50	32.30
S ₄ D ₂	48.37	46.50	44.80	43.20	42.80	41.70	41.10	39.50	38.30	30.00	29.60	28.60	27.90
S ₄ D ₃	48.37	46.90	45.60	44.70	43.70	42.50	41.30	40.00	38.50	37.00	35.60	33.60	29.80
SEm±	1.16	1.11	1.06	1.03	1.05	1.00	0.87	0.83	0.77	0.76	0.77	0.72	0.64

(continued on next page)

Crop Residues	Period of composting (days)												
	0	10	20	30	40	50	60	70	80	90	100	110	120
CD($P = 0.05$)	3.41	3.26	3.10	3.01	3.09	2.94	2.54	2.42	2.27	2.22	2.25	2.12	1.88
CV (%)	4.04	3.97	3.91	4.02	4.27	4.34	3.93	3.90	3.77	3.92	4.19	4.18	3.84

S₁: Paddy straw S₂: *Sesamum* stalks S₃: Redgram stalks S₄: Cotton Stalks

D₁: Control D₂: decomposer-1 D₃: decomposer-2

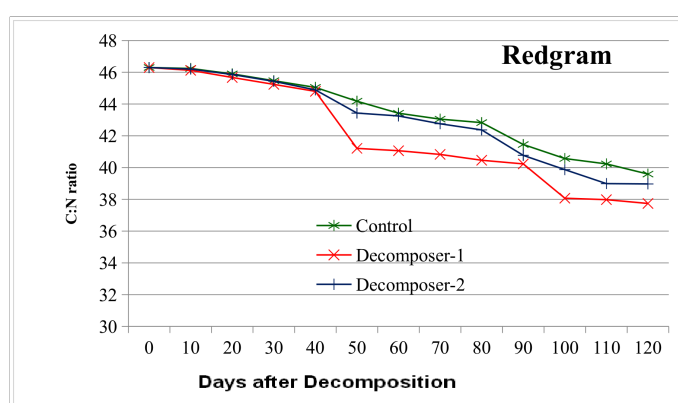
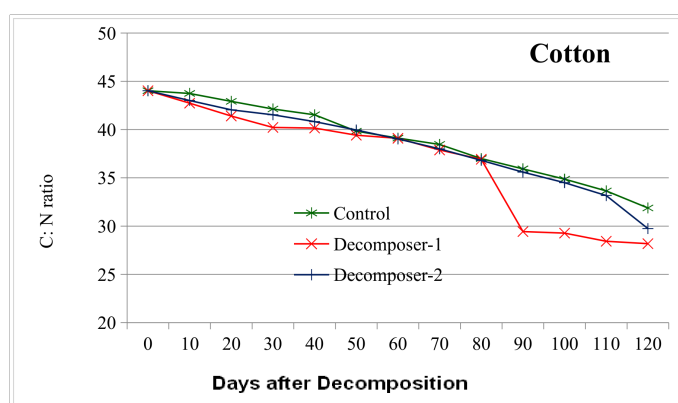
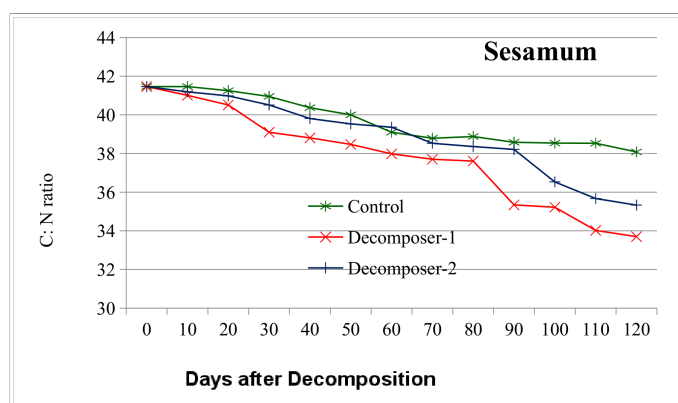
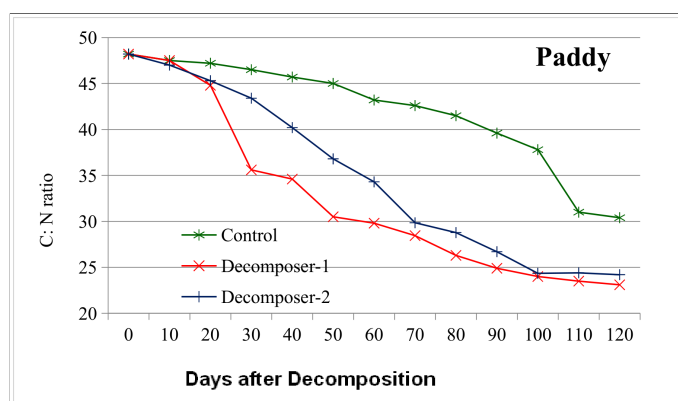


Figure 1. C:N ratio of composting material as influenced by crop residues and decomposers

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