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Microbial Consortia: Sustainable Alternative to Maize Residue Burning and Way to Enhance Nitrogen in Calcareous Soil

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Abstract: Crop residue burning is a major environmental problem that causes air pollution and greenhouse gas emissions. This study aimed to evaluate the effect of microbial consortia and nutrient boosters (urea and jaggery) on maize residue decomposition and nitrogen mineralization in calcareous soil. Thirteen treatments with different combinations of microbial consortia, urea, jaggery and residue application methods (surface or incorporation) were compared with a control (soil only) in a laboratory incubation experiment. The microbial consortia and nutrient boosters significantly increased the available nitrogen content in soil compared to the control and treatments with only residue. The highest increase (21.9%) was in the treatment with incorporated residue, 1% consortia, 1% urea, and 2% jaggery. This treatment also achieved the highest rate of nitrogen mineralization. Incorporation of residue and amendments generally resulted in higher nitrogen availability than surface application. Meanwhile, microbial consortia degraded the high carbon and nitrogen (C:N) ratio maize residue and released mineral nitrogen to the soil. Furthermore, urea and jaggery provided nitrogen and carbon sources for the microbes, boosting nitrogen availability. Therefore, these findings suggest that microbial consortia, urea, and jaggery are effective amendments for enhancing nitrogen availability from maize residue in soil, and can provide a sustainable alternative to residue burning by accelerating decomposition and nutrient mineralization.

Keywords: Microbial consortia, Nutrient boosters, Maize residue, Nitrogen mineralization, Calcareous soil

Maize is India's third most important cereal crop after rice and wheat. India ranks 4th in the world in terms of maize cultivation area and 7th in production, accounting for approximately 4% of global maize area and 2% of the total production (Kaur et al 2023). From 1950-51 to 2018-19, India's maize production has seen a significant increase from 1.73 million MT to 27.8 million MT, marking an almost 16-fold growth. The average yield has improved from 547 kg/ha to 2965 kg/ha, a more than 5-fold increase, while the cultivation area has expanded nearly threefold (AICRIP 2020). In India, maize is primarily cultivated in two seasons: rainy (*kharif*) and winter (*rabi*). Kharif maize accounts for approximately 83% of the maize area, with rabi maize covering the remaining 17%. A significant portion of the kharif maize area, exceeding 70%, is grown under rainfed conditions.

However, a challenge arises in the continuous cropping system. After harvesting *kharif* maize, farmers need to prepare the field for rabi maize. This necessitates the removal of leftovers after harvest for field preparation and prompt sowing of the next crop (Kumar et al 2023). The two main options for residue management are either burning or incorporating the residues into the soil (Bamboriya et al 2020). Burning poses environmental issues, producing global warming gases and causing severe pollution. India, the second largest agro-based economy with year-round crop cultivation, generates a large amount of agricultural waste, including crop residues (Bhuvaneshwari et al 2019). In the absence of adequate sustainable management practices, approximately 40-60 percent of crop waste is burned every year in India, causing excessive particulate matter emissions and air pollution (Huang et al 2022). Crop residue burning has become a major environmental problem causing health issues as well as contributing to global warming (Deshpande et al 2023). On the other hand, incorporating residues into the field takes more time for decomposition due to the wider carbon and nitrogen ratio of crop residue. This can initially immobilize mineral nutrients, especially nitrogen, leading to nutrient deficiencies in growing crops (Meena et al 2020). To address these challenges, a solution involves applying extra nitrogen fertilizer, but this can exacerbate volatilization and nutrient losses due to high temperatures. In-situ crop residue incorporation, composting and mechanization are a few effective sustainable techniques that can help to curtail the issue while retaining the nutrients present in the crop residue in the soil (Kaur and Singh 2022). There is a need for a supporting platform to solve issues such as crop residue burning.

In response to these concerns, a strategy has been developed. Lignin and cellulose-degrading microbial consortia were prepared to enhance maize residue decomposition and nutrient mineralization in calcareous soil. The objective of the experiment to study aims to investigate the impact of prepared microbial consortia on both maize residue decomposition and nitrogen mineralization in calcareous soil. Additionally, it seeks to evaluate how the method of microbial consortia application, whether surface or soil incorporation, influences nitrogen mineralization and its rate in the same soil type. This innovative approach aims to expedite residue decomposition, minimize nutrient deficiencies, and reduce the window period for sowing the next crop.

MATERIAL AND METHODS

Soil and crop residue samples for the incubation experiment were collected at 11°00'55"N 76°56'15"E from the Eastern block farm of Tamil Nadu Agricultural University (TNAU), Coimbatore, Tamil Nadu, India. The soil is classified as *Vertic ustropept*, belonging to the Inceptisol order and Periyanaickenpalayam soil series. It is a mixed black calcareous, fine, montmorillonitic, isohyperthermic soil. The soil sample was collected from the 0–15 cm depth layer using a metal core sampler and air-dried under shade, processed then sieved through a 2-mm mesh and divided into two subsamples. One subsample was used for the laboratory incubation experiment and other subsample was used for the determination of physical and chemical properties following standard methods (Table 1). Cellulose and lignin was determined and listed in Table 2 (Sadasivam 1966)

Table 1. Initial characteristics of the soil used for the incubation study

Soil properties	Mean
pH (1:2.5 soil: water)	8.34
EC (dS m^{-1}; 1:2.5 soil: water)	0.45
Total carbon (%)	0.71
Oxidizable organic carbon (%)	0.43
Available N (kg ha^{-1})	267
Available P (kg ha^{-1})	17.54
Available K (kg ha^{-1})	356
Total N (%)	0.13
Bulk density (Mg m^{-3})	1.45

Incubation experiment: An incubation experiment was conducted at Department of Soil Science and Agricultural Chemistry, TNAU, Coimbatore during 2022 to determine nitrogen mineralization and to evolve a technology to enhance the minerlaization potential and to increase the nutrient releasing capacity. Including absolute control, there were 13 treatments, namely residue alone, residue + microbial consortia, residue + microbial consortia + nutrient boosters (different rates urea and jaggary) and they were applied under two methods *viz.,* either on the surface or incorporated into the soil (Table 3). The treatments were replicated thrice. The microbial consortium was prepared by isolating bacteria and fungi from native soil using serial dilution techniques. Efficient cultures were combined to form the consortium for this study. Nutrient boosters, namely urea and jaggery, served as an initial nutrient source—comparable to "ready-to-serve" food—for the microbial consortia. This strategy supported their survival and multiplication and helped prevent immobilization during the early stages of crop residue decomposition.

Approximately 1000 g of air-dried, 2 mm sieved soil was treated with separate crop residues of cotton, maize, and cowpea, mixed in ratios of 4.6 g, 5.2 g, and 0.78 g, respectively. These ratios are equivalent to the dry matter yields of 10.4 tonnes, 9.1 tonnes, and 1.6 tonnes per hectare for cotton, maize, and cowpea, respectively. The soil was then mixed with the specified quantities of microbial consortia and nutrient boosters. For surface application, each residue was placed on the soil surface, while for incorporation, the residues were thoroughly mixed into the soil. Water was added to reach field capacity, and the samples were incubated at 30±2°C for 120 days in a laboratory incubator. The treated samples were maintained at field capacity (28.8%, w/w) throughout the incubation period, with water loss due to evaporation compensated by adding distilled water at each sampling interval. Soil samples were collected at 0, 7, 15, 30, 60, 90, and 120 days of incubation and analyzed for inorganic nitrogen (NH4+ -N and NO3- -N).

To assess nitrogen mineralization, inorganic nitrogen (NH4+ -N and NO3- -N) was extracted with a 2 M KCl solution at a 1:10 soil-to-solution ratio at the end of each incubation period. NH4+ -N was determined by steam distillation with magnesium oxide (MgO) in a micro-Kjeldahl distillation unit (Keeney and Nelson 1982). The same procedure was

Table 2. Initial chemical characteristics of the crop residues used for the study

Residue type	Total C (%)	Total N (%)	C/N ratio	Cellulose (%)	Lignin (%)	Hemicellulose (%)
Maize	41.32	0.86	48.0	31.21	13.18	24.12

applied for NO3- -N after reduction with Devarda's alloy. The amount of N mineralized (NH4+ -N and NO3- -N) at a given time 't' was calculated by subtracting the mineral-N content (NH4+ -N and NO3- -N) of the soil at the start of incubation from the mineral N at time 't'.

Statistical analysis: The study used SPSS 21.0 software (IBM) to analyze the significant interaction among the method of application, microbial consortia, and duration. The interaction was also visually represented by a violin plot for total mineral nitrogen mineralization, which was analyzed using GraphPad Prism software. Mean comparisons were conducted using the LSD post-hoc test, which compared all possible pairs of means (McKnight et al 2020).

RESULTS AND DISCUSSION

The experiment demonstrated significant influences of application method, incubation duration, and their interaction on NH_4^+-N content in maize residue. Treatments with microbial consortia, urea, and jaggery (T_6-T_{13}) exhibited higher NH_4^+-N content than the control (T_1) and treatments with only soil and residue (T_2, T_3). Treatments incorporating microbial consortia and nutrient boosters exhibited higher ammonical nitrogen content than the control and treatments with only maize residue or residue + consortia (Fig. 1). The treatments with 1% consortia, 1% urea, and 2.0% jaggery (T_9) and 1% consortia + 1% urea + 1.5% jaggery (T_{13}) recorded the highest NH_4^+-N values (45.71 and 43.12 mg/kg, respectively) on the 45th day, indicating their effectiveness in enhancing nitrogen mineralization. NH_4^+-N content initially increased up to the 45th day, followed by decreases in T_{10}, T_{11}, T_{12}, and T_{13}, possibly due to a balance between mineralization and immobilization processes (Ali et al 2021). Surface application (T_2) and consortia (T_4) showed negative values up to 40 and 35 days, respectively, while residue incorporated soil (T_3, T_5) showed negatives up to 35 and 30 days, indicating net immobilization. T_2 and T_4 turned positive from the 30th day, indicating free NH_4^+-N (Fig. 1 and Table 5).

In treatments with residue alone or residue + consortia, the inorganic nitrogen (N) concentrations decreased and were much lower than in the control up to 30 days after incubation. This suggests that adding high C:N ratio residue stimulated microbial growth and N immobilization, especially in the initial days of the experiment. T_6 to T_{13} consistently showed positive values, indicating ammonification and NH_4^+-N release. Both surface application and incorporation of maize residue with microbial consortia and nutrient boosters showed similar N mineralization trends up to the 45th day, followed by a slight decrease up to the 75th day. Khali et al (2005) and Rosenkranz et al (2012) observed that N mineralization was dominated by ammonification during the first 30 days after incorporating crop residues. Thereafter, NH_4^+-N released from the ammonification was nitrified to NO_3^--N, which could explain the declining trend of NH_4^+-N after 45 days of incubation in surface applied and residue incorporated soil. Method of application also significantly affected the NH_4^+-N mineralization (Abiven and Recous

Table 3. Treatment details

Treatments	Surface application
T_1	Control
T_2	Soil + Crop residue
T_3	Soil + residue + Microbial consortia (1%)
T_4	T_3 + Nutrient Booster (0.5% Urea + 1.5% Jaggery)
T_5	T_3 + Nutrient Booster (0.5% Urea + 2.0% Jaggery)
T_6	T_3 + Nutrient Booster (1.0% Urea + 2.0% Jaggery)
T_7	T_3 + Nutrient Booster (1.0% Urea + 1.5% Jaggery)
Incorporated into soil	
T_8	Soil + Crop residue
T_9	Soil + residue + Microbial consortia (1%)
T_{10}	T_3 + Nutrient Booster (0.5% Urea + 1.5% Jaggery)
T_{11}	T_3 + Nutrient Booster (0.5% Urea + 2.0% Jaggery)
T_{12}	T_3 + Nutrient Booster (1.0% Urea + 1.5% Jaggery)
T_{13}	T_3 + Nutrient Booster (1.0% Urea + 2.0% Jaggery)

Table 4. Percentage increase of available nitrogen in soil after 90 days of maize residue application with microbial consortia, urea, and jaggery

Treatments	% increase over control
T1- Control	-
T2- Soil + residue (Surface	5.6
T3- Soil + Residue (incorporated)	6.7
T4- Soil + residue + 1% consortia (S)	9.7
T5- Soil + residue + 1% consortia (I)	10.8
T6- Soil + residue + 1% consortia + 0.5% Urea + 1.5% Jaggery	14.1
T7- Soil + residue + 1% consortia + 1% Urea + 1.5% Jaggery	14.5
T8- Soil + residue + 1% consortia + 0.5% Urea + 2.0% Jaggery	13.4
T9- Soil + residue + 1% consortia + 1.0% Urea + 2.0% Jaggery	16.0
T10- Soil + residue + 1% consortia + 0.5% Urea + 1.5% Jaggery	13.8
T11- Soil + residue + 1% consortia + 1% Urea + 1.5% Jaggery	19.3
T12- Soil + residue + 1% consortia + 0.5% Urea + 2.0% Jaggery	17.1
T13- Soil + residue + 1% consortia + 1.0% Urea + 2.0% Jaggery	21.9

2007). The incorporating residues with soil enhanced the N mineralization .Gupta et al (2010) also reported that the N release from surface residues was reduced compared to sub-surface placement.

The decrease in NH_4^+-N content at day 15 for T_2 and T_3 indicated increased microbial activity, potentially leading to enhanced immobilization rates. This indicate that the initial plant residue quality influenced the N mineralization in crop residues, and that the high C:N ratio of maize residue caused immobilization (Chaves et al 2021). However, T_9 and T_{13}, with increased urea and jaggery content, showed a stable NH_4^+-N content throughout the experiment, possibly due to reduced nitrification via heterotrophic denitrification stimulated by jaggery. Urea can provide a readily available source of nitrogen, and jaggery can stimulate the microbial activity and carbon supply (Krausfeldt and Marz et al 2020). These results are also supported by the findings of previous studies. Nishio and Oka (2003) reported that incorporating rice and wheat straw enhanced the immobilization of both nitrate and ammonium because the high C:N ratio did not meet the microbial N requirements. The slight increase in NH_4^+-N is mainly due to the decline in the C:N ratio of the decomposing crop residue; once the crop residue C:N ratio is less than 21:1, the microbial N will be mineralized (Walley and Yates 2002).

Nitrate nitrogen: The NO_3^--N content in maize residue increased significantly in all treatments regardless of the method of residue application (Table 6, Fig. 2). The highest nitrification was in T_{13} (soil + residue + 1% consortia + 1.0% urea + 2.0% jaggery) with 71.23 mg/kg of NO_3^--N at 45th DAI, followed by T9 (soil + residue + 1% consortia + 1.0% urea + 1.5% jaggery) with 67.95 mg/kg at 60th DAI. Nutrient boosters provided a ready-made food source for microorganisms, enhancing their activity and leading to higher mineralization and nitrification. Immobilization occurred on the 15th day after incubation in T_4 (soil + residue + consortia). T_2 (soil + residue) also recorded immobilization (6.45 mg/kg of NO_3^--N) compared to T_1 (soil) (7.32 mg/kg) but later progressed to NO_3^--N mineralization until the end of the incubation period. Anguria et al (2017) indicated that plant residues with low biochemical quality tend to initiate decomposition slowly due to immobilization of nutrients, especially N, at the early phase of their decomposition. Nitrate content increased up to 45 days in all treatments, followed by a decreasing trend that stabilized afterwards. This pattern reflects the release of N from decomposable residue fractions, subsequent utilization by soil microbes,

Table 5. Effect of maize residue and microbial consortia on ammonium nitrogen (NH_4^+-N mg/kg) dynamics over incubation time

Treatments	Surface applied residues						Treatments	Residues incorporated with soil					
	Incubation intervals (days)							Incubation intervals (days)					
	15	30	45	60	75	90		15	30	45	60	75	90
T_2	-6.38*	-1.64	2.47	0.81	3.00	2.40	T_3	-6.00	-0.70	6.56	2.53	4.38	2.99
T_4	-8.52	-5.23	4.29	9.22	8.77	8.10	T_5	-9.63	-2.82	5.90	11.82	11.33	8.97
T_6	8.39	10.07	18.60	14.77	14.72	12.53	T_{10}	8.21	13.08	23.24	17.38	17.07	14.67
T_7	10.11	15.82	21.03	17.84	17.49	17.07	T_{11}	11.70	16.81	24.00	19.32	18.82	18.68
T_8	8.57	13.70	19.82	14.93	14.86	16.93	T_{12}	10.43	14.61	20.13	16.28	16.08	15.73
T_9	11.63	17.39	21.12	17.18	16.89	24.91	T_{13}	13.09	19.69	26.59	22.88	22.02	21.40

*negative values indicate immobilization of nitrogen

Table 6. Effect of maize residue and microbial consortia on nitrate nitrogen (NO_3^--N) dynamics over incubation time

Treatments	Surface applied residues						Treatments	Residues incorporated with soil					
	Incubation intervals (days)							Incubation intervals (days)					
	15	30	45	60	75	90		15	30	45	60	75	90
T_2	-0.87	2.9	6.03	7.99	5.87	3.83	T_3	-1.43	3.49	6.45	8.82	6.36	5.05
T_4	-1.18	3.97	7.23	9.49	10.05	9.02	T_5	-1.06	5.71	8.69	11.92	13.27	10.52
T_6	14.13	27.95	37.7	38.05	30.84	28.92	T_{10}	15.52	29.96	39.42	38.05	31.14	30.23
T_7	22.44	42.17	50.62	57.96	50.12	47.5	T_{11}	23.29	47.22	59.95	58.18	52	52.32
T_8	14.55	29.18	40.65	39.78	30.43	28.82	T_{12}	15.81	30.41	43.23	45.13	36	34.6
T_9	23.1	44.25	53.88	60.89	50.81	52.2	T_{13}	24.22	50.31	63.66	69.37	63.93	62.91

*negative values indicate immobilization of nitrogen and decomposition of more recalcitrant residue components.

Treatments T_9 and T_{13}, surface applied and incorporated with soil, respectively, displayed the highest NO_3^--N content throughout the incubation period emphasizing their effectiveness in promoting N mineralization from maize residue(Table 6, Fig. 2). The high carbon and nitrogen ratio of maize residue in T_2 might have limited N availability for microbial metabolism, resulting in immobilization. However, as days progressed, mineral nitrogen release increased significantly in both methods of residue application. Treatments with soil + residues + nutrient boosters (urea and jaggery) significantly increased nitrification throughout the incubation period in both surface and incorporation methods. This study evidenced that higher urea and jaggery levels (1% vs. 0.5%, 2% vs. 1.5%) mineralized higher NH_4^+-N and NO_3^--N content in maize residues. This suggests that these

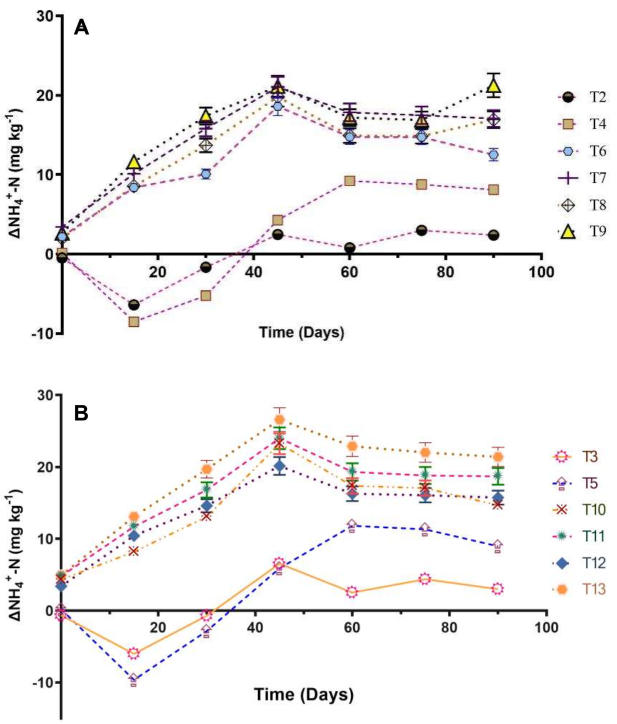

Fig. 1. Temporal dynamics of NH_4^+-N content (mg/kg) in maize crop residues: **A)** Surface applied **B)** Incorporated with soil

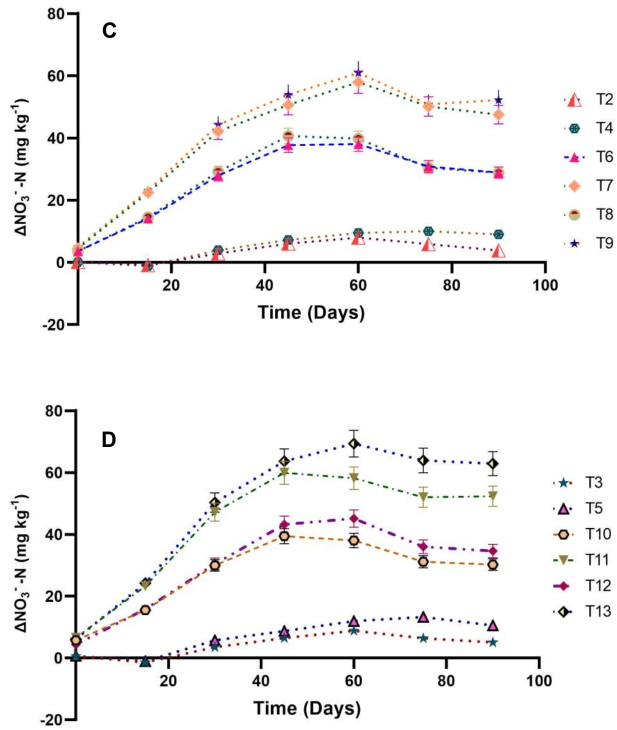

Fig. 2. Temporal dynamics of NO_3^--N content (mg/kg) in maize crop residues: **C)** Surface applied **D)** Incorporated with soil

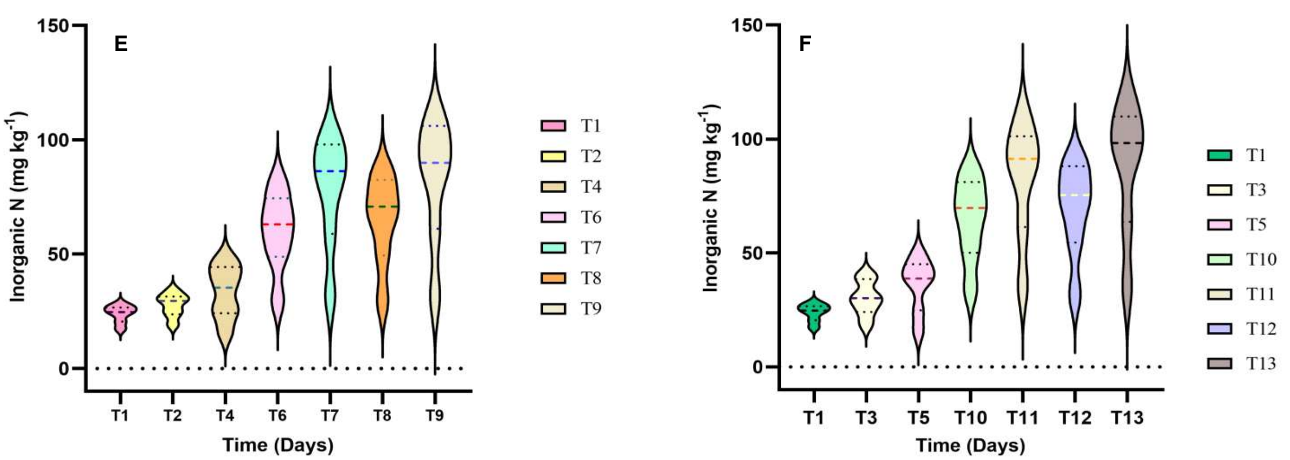

Fig. 3. Total mineral nitrogen mineralization (mg/kg) from maize crop residues: **E)** Surface applied **F)** Incorporated with soil

nutrients were limiting factors in the decomposition process. The addition of microbial consortia, urea, and jaggery can affect these factors and stimulate nitrification. However, the presence of organic carbon sources, like jaggery, may also inhibit nitrification by competing with nitrifying bacteria for oxygen and lowering soil pH.

NH_4^+-N and NO_3^--N concentrations were significantly higher in incorporated treatments than in surface applied treatments. This is due to the high contact between soil and residues in incorporated treatments, while adding consortia with nutrient boosters, the organisms proliferated more and enhanced the mineralization of both NH_4^+-N and NO_3^--N. The NH_4^+-N concentration was higher than the NO_3^--N concentration in the first 45 days, accounting for 70% of total inorganic N. This is in agreement with Kara (2000), where proteins and amino acids from crop residues are first converted to NH_4^+-N before being nitrified to NO_3^--N in the presence of oxygen. The high concentration of NH_4^+-N in the first 45 days, together with decarboxylation of organic acid anions, may explain the strong increase in soil pH of the residue treatments (Table 5, Fig. 1). From day 45, the lower percentage of total inorganic N as NH_4^+-N, as well as the increase in NO_3^--N concentrations (Fig. 2), suggests that nitrification became more important. The strong increase of nitrate nitrogen concentrations in consortia, nutrient boosters and residue incorporated treatments after 45th day resulted in significant decrease of soil pH, due to the proton release during nitrification

Violin plot result: The violin plot shows the changes in total mineral nitrogen (TMN) content in soil over 90 days for 13 treatments (Fig. 3). Treatments with microbial consortia and nutrient boosters (T_6-T_{13}) had higher TMN than the control (T_1) and treatments with only residue (T_2 and T_3), indicating enhanced nitrogen mineralization from maize residue. TMN increased for all treatments until day 45, then decreased or stabilized, reflecting microbial decomposition and nitrogen utilization. Treatments T_9 and T_{13}, with 1% consortia, 2% jaggery, and 1% consortia, 1% urea, 1.5% jaggery, respectively, displayed the highest TMN, affirming their substantial nitrogen mineralization potential. In contrast, treatments with only residue (T_2 and T_3) showed net TMN immobilization at first, followed by gradual mineralization from day 30, indicating microbial consumption followed by residue decomposition and nitrogen release. The results highlight the significant enhancement of nitrogen mineralization from maize residue in soil with microbial consortia and nutrient boosters. The combination of 1% consortia with 2% jaggery or 1% consortia, 1% urea, and 1.5% jaggery was the most effective in this study. Soil N availability may be important for residue decomposition. The soils with maize residue alone had lower cumulative N mineralization than unamended soil. The addition of microbial consortia and nutrient boosters resulted in higher mineral N than unamended soil; the cumulative mineral N for residues incorporated with soil was higher than for residues applied on soil surface.

Percentage increase over control: The highest percentage of available nitrogen increase over control was in T_{13} and T_{11} with 21.9% and 19.3%, respectively (Table 4). The lowest percentage of available nitrogen increase over control was in T_2 and T_3 with 5.6% and 6.7%, respectively. The incorporation of residue and amendments resulted in higher percentage of available nitrogen increase over control than the surface application of the same treatments. The result suggests that the combined application of microbial consortia, urea, and jaggery can enhance the nitrogen availability in soil, and that the incorporation of these amendments can improve the nitrogen use efficiency. Available nitrogen in T_6 to T_{13} was significantly higher than in the control and residue alone treatments, suggesting that the microbial biomass took up the ready source food from nutrient boosters and mineralized the nutrients from maize residue to the soil. Marz et al (2020) achieved maximum mineralization by adding an additive nutrient source.

CONCLUSION

Microbial consortia and nutrient boosters (urea and jaggery) increased the available nitrogen content in soil compared to the control and treatments with only residue. The highest increase was in incorporated residue with 1% consortia, 1% urea, and 2% jaggery. Incorporation generally resulted in higher increases than surface application. This indicates that incorporation improved soil-residue contact and microbial activity, enhancing N mineralization. Microbial consortia degraded the high C:N ratio maize residue and released mineral nitrogen to the soil. Urea and jaggery provided N and C sources for the microbes, boosting N availability. These results suggest that microbial consortia, urea, and jaggery were effective amendments for increasing N availability from maize residue in soil. Therefore, the acceleration of decomposition through the application of lignolytic consortia and the simultaneous mineralization of the nutrient from residue will synchronize the nutrient requirement of the upcoming crop. Consequently, this might be an alternative way to enhance soil ecology through avoiding huge chemical fertilizers and incorporation of crop residues instead of residue burning.

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