Nitrogen

Article

Nitrogen Dynamics from Conventional Organic Manures as Influenced by Different Temperature Regimes in Subtropical Conditions

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Abstract: Determining nutrient-release patterns of organic manures can give an estimate of the potential amount of nutrients that a given material can contribute to crops along with chemical fertiliser. Nutrients released from organic manure depend on several factors, and temperature is one of them. To evaluate how different types of conventional organic manures release nitrogen (N) under varying temperature conditions, an incubation study was conducted at the Bangladesh Agricultural Research Institute. Six organic manures—poultry manure (PM), vermicompost (VC), bio-slurry (BS), cowdung (CD), water-hyacinth compost (WHC), and rice straw compost (RSC)—were evaluated at three temperature regimes (15, 25, and 35 °C) to study the dynamics of N incubated for 330 days. The N release was significantly influenced by the interaction of organic manures and temperature regimes. Poultry manure-treated soil incubated at 35 °C had the highest mineralisation of all parameters than other manures. The mineralisation of N followed the order: PM > VC > BS > CD > WHC > RSC > control and 35 °C > 25 °C > 15 °C. Across different temperatures, the mineralisation rate of PM was 15–55% higher than that of other manures. At 35 °C, the mineralisation rate was 10% and 20% higher compared to 25 °C and 15 °C, respectively. The first-order kinetic models predicted the organic N release from manures satisfactorily. The findings of the present study enrich the understanding of N-release patterns under different temperature regimes that prevail in different crop growing seasons in Indo-Gangetic Plains, providing valuable data for researchers and policymakers interested in sustainable integrated nutrient management practices.

Keywords: decomposable rate constant; first-order kinetic model; N release; poultry manure; vermicompost

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1. Introduction

Soil productivity relies on various factors, including soil characteristics, climate, agronomic practices, and nutrient availability. In South Asia, particularly in Bangladesh, soil fertility decline has become a major problem for crop cultivation [1,2]. The intensification of cropping practices has worsened the situation, as crop uptake of nutrients now exceeds yearly replenishment by fertilisation [3]. Contemporary agricultural systems have also catalysed the gradual deterioration of soil structure and the depletion of soil organic matter (SOM) [2,4–6].

In Bangladesh, from 1969 to 2010 and from 2010 to 2020, SOM depletion varied greatly across the agro-ecological zone, ranging between 9% and 70% [2,3]. The most pronounced

losses have been observed in the High Ganges River Floodplain, Old Meghna Estuarine Floodplain, and the Northern and Eastern Hills ([7,8] Shil et al. 2016; Kumar et al. 2019). Alarmingly, certain soils now exhibit SOM levels reducing below the 10 g kg^{-1} threshold [3]. The depletion of organic matter in Bangladeshi soils has led to concerns among farmers about soil fertility and its impact on crop production [9] (Uddin et al., 2022). However, it is worth noting that some soils have stabilised their OM levels through crop rotation practices and rice-based cropping systems [2].

With an aim to enhance SOM levels in soils and practice both organic and inorganic fertilisation simultaneously (e.g., integrated nutrient management), farmers have resorted to a diverse array of organic amendments [3]. Organic fertilisers such as compost and manure enhance soil microbial activity and improve soil health, promoting biodiversity. They are often sourced locally and are less expensive than synthetic fertilisers in the long term. They can help sequester carbon in the soil, aiding in climate change mitigation by storing carbon in the soil and reducing greenhouse gas emissions [3].

These invaluable resources encompass cowdung, poultry manure [10], rice straw including rice husk and rice brans, wheat straw [11], water hyacinth [12], leaf litter [10], household waste, biogas slurry [13], vermicompost [14], sugarcane trash [15], oil cakes, and a host of others. It is worth noting that cowdung is a significant source of organic matter, but some of it is used as fuel. Incorporating animal and plant residues into the soil enriches the soil's organic carbon (OC) content and bolsters nutrient availability, resulting in enhanced crop yields [16].

Poultry manure, distinguished by its richness in nitrogen (N) and phosphorus (P), undergoes rapid mineralisation immediately upon application, not only promotes robust plant growth but also augments soil properties, including improved structure, heightened water-holding capacity, enhanced aeration, and optimised drainage [17,18]. In contrast, vermicompost adopts a more gradual and protracted approach to nutrient release, ensuring a sustained supply of nutrients to plants over an extended period [19]. On a parallel front, vermicompost, derived through the labor of earthworms, offers a harmonious blend of essential plant nutrients such as organic carbon (OC), nitrogen (N), phosphorus (P), and potassium (K) [20]. The nutrient release dynamics of water hyacinth further emphasise its green potential due to its propensity for rapid nutrient release compared to other plant residues [12].

The proper utilisation of these varied organic resources relies on a comprehensive understanding of nutrient mineralisation dynamics, with a particular emphasis on nitrogen—a crucial element essential for plant growth. The process of mineralisation of N is influenced by various factors, such as fluctuations in temperature, soil composition, and the type of organic materials. Elevated temperatures precipitate accelerated decomposition, with mineralisation rates doubling for every 18 °F increase [21]. Crucially, before plants can assimilate organic N, they must first undergo conversion into inorganic forms through microbial-mediated processes, collectively known as mineralisation. This intricate interplay between soil microbial activity and mineralisation shows significant temperature dependence, highlighting the crucial role of temperature in nutrient cycling [22].

In light of these complexities, the carbon–nitrogen (C:N) ratio emerges as a crucial factor in nutrient mineralisation in organic fertilisers. Lower C:N ratios promote nutrient release, while higher ratios induce immobilization [23,24]. Furthermore, environmental variables such as soil water content and temperature exert significant influence on the degradation of organic matter under arable farming conditions [25]. The pursuit of forecasting N mineralisation in organic fertilisers has led to various methods, each relying on different quality parameters [7].

Proper management of N sources is critical for optimising crop yield while minimising negative environmental impacts. Integrating synthetic fertilisers, organic amendments, and leguminous crops can create a more sustainable agricultural system. Adoption of practices that enhance N-use efficiency will not only improve crop productivity but also promote ecological balance and soil health [7].

A comprehensive understanding of organic fertiliser mineralisation is crucial in subtropical regions with intensive cropping systems [7]. In this context, this research assessed N release from commonly used organic manures in Bangladesh. By exploring the various aspects of nitrogen mineralisation", considering temperatures, soil types, and the compositional attributes of organic materials, the present study provides insights into nutrient management strategies which can help increase crop productivity and the adoption of sustainable integrated nutrient management practices. The study was therefore conducted to evaluate the decomposition and N-release pattern of some organic manures in soil under temperature regimes and predict annual N mineralisation using first-order kinetic models [26]. We predicted that different organic manures and temperature regimes would greatly impact N mineralisation.

2. Materials and Methods

2.1. Soil Sampling for Incubation Study

The incubation experiment was carried out at the Micronutrient Laboratory, Soil Science Division, Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur, from 2018 to 2019. Soils for the study were collected at a depth of 0–15 cm from the soil physics experimental field (23°24′13″ N; 90°24′22″ E), Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur. The site belongs to the Chhiata series of the agro-ecological zone, Madhupur Tract (AEZ 28). Immediately after collection, undecomposed plant materials were removed by hand, and the soil was sieved (<2 mm), kept for 24 h, and covered with a polythene sheet after adjusting the moisture level to 40% water holding capacity. The details can be found in Mondol et al. [27].

Soils with 40% water holding capacity were subjected to pre-incubation aerobically at room temperature for 10 days. Pre-incubation was performed in a plastic container; this allowed the microbial population to stabilise, minimising the effects of soil handling and preparation. Immediately after conditioning, the soil was used for the organic matter decomposition and nutrient-release pattern experiment [27]. The morphological, physical and chemical properties of soils are given in Tables 1 and 2.

Table 1. Morphological characteristics of the experimental field.

Morphological Characteristics	
Locality	BARI, Joydebpur, Gazipur
Geographic position	23°24′13″ N Latitude, 90°24′22″ E Longitude,
Altitude	14.6 m high above the sea level
Agro-Ecological Zone (AEZ)	Modhupur Tract (AEZ 28)
General Soil type	Grey Terrace Soils (*Aeric Albaquept*)
Taxonomic soil classification	
Order	Inceptisol
Suborder	Aquept
Subgroup	*Aeric Albaquept*
Soil series	Chhiata
Physiographic unit	Madhupur Tract
Drainage	Moderate
Flood level	Above flood level
Topography	Medium high land

2.2. Collection and Processing of Compost

As detailed in Mondol et al. [27], poultry manure (PM), vermicompost (VC), bio-slurry (BS), cowdung (CD), water hyacinth compost (WHC) and rice straw compost (RSC) were used as organic materials. PM, BS, and CD were collected from Pazulia village, Gazipur Sador, Gazipur. VC, WHC, and RSC were collected from the Soil Science Division, BARI, Joydebpur, Gazipur. The samples were then brought to the Soil Science laboratory, BARI, Joydebpur, Gazipur and cleaned and dried under open sunlight, followed by oven drying

at 60 °C for 48 h and ground in a steel grinding mill containing a fine sieve. Prepared samples were stored in desiccators before using for incubation. The experiment was laid out in a completely randomised design (CRD) with three replications. Different nutrient contents (Table 3) of all the composts were tested before starting the incubation study following the methods mentioned in Table 4.

Table 2. Physical and chemical properties of soil in the experimental field.

Physical Properties	**Values**
Sand (%)	27.18
Silt (%)	38.30
Clay (%)	34.52
Textural class	Clay loam
Particle density (g cm^{-3})	2.48
Bulk density (g cm^{-3})	1.42
Porosity (%)	42.74
Chemical properties	
pH	6.5
Organic C (%)	0.85
Organic matter (%)	1.47
Exchangeable K (cmol kg^{-1} soil)	0.18
Exchangeable Ca (cmol kg^{-1} soil)	4.80
Exchangeable Mg (cmol kg^{-1} soil)	2.10
Total N (%)	0.07
Available N (µg g^{-1} soil)	50.00
Available P (µg g^{-1} soil)	12.93
Available S (µg g^{-1} soil)	15.00
Available Zn (µg g^{-1} soil)	0.71
Available B (µg g^{-1} soil)	0.26

Table 3. Contents of nutrient elements in different organic manures.

Manures	**C**	**N**	**P**	**K**	**S**	**C:N**	**C:P**	**C:S**
			(%)					
PM	25	2.32	2.18	1.45	0.44	10.8	11.5	56.8
VC	28	1.90	1.70	1.40	0.38	14.7	16.5	73.7
BS	29	1.48	1.25	1.24	0.31	20.0	23.2	93.5
CD	34	1.32	0.29	0.75	0.27	25.8	117	126
WHC	40	0.80	0.13	0.80	0.05	50.0	308	800
RSC	42	0.60	0.07	0.85	0.05	70.0	600	840
Manures	Ca	Mg	Na	Cu	Fe	Zn	Mn	B
		(%)				(µg g^{-1})		
PM	1.59	1.02	0.58	220	680	266	300	105
VC	1.10	0.55	0.36	105	651	115	325	113
BS	1.36	0.45	0.30	155	701	216	310	154
CD	1.05	0.47	0.26	96	690	132	252	142
WHC	1.00	0.39	0.23	90	812	38.6	305	170
RSC	0.81	0.29	0.15	45	317	30.9	234	23.0

Poultry manure = PM, Vermicompost = VC, Bio-slurry = BS, Cowdung = CD, Water hyacinth compost = WHC, and Rice straw compost = RSC.

2.3. Incubation Experiment

The laboratory incubation experiment was conducted to investigate the effect of different sources of organic amendments (viz. PM, VC, BS, CD, WHC and RSC) on N mineralisation using a Memmert incubator, GmbH+Co. KG, Hbk25 Frankfurt Am Main, HE 60549, Germany. For this experiment, organic materials were added to the soil at the

rate of 2 g 100 g^{-1} soil (dry weight basis) and placed in a 100 mL glass jar. Each treatment had three replications. Following the amendment, glass jars were placed in 1 L dark glass bottles, sealed and incubated at three different temperatures at 15 °C, 25 °C, and 35 °C and placed in an incubator for 330 days. To maintain the internal humidity of the 1 L glass bottle, 10 mL distilled water was added at the bottom of each bottle. Available N was determined after 5, 10, 15, 20, 30, 40, 60, 90, 120, 180, 240, and 330 days of incubation. More details are given in Mondol et al. [27].

Table 4. Methods used for chemical properties of soils.

Name of Parameter	Methods
1. pH	Glass-electrode pH meter, the soil–water ratio is 1:2.5, as described by Page et al. [28].
2. Organic carbon	Wet digestion method [29].
3. Total N	Micro-Kjeldahl method [30].
4. Available N (NH_4^+ and NO_3^-)	The ammonium form of N was determined by leaching the soil with 1 N KCl. The NO_3-N was determined by reducing the nitrate to ammonia by Devarda's alloy in an alkaline solution (40% NaOH) [31,32].
5. Available P	Available phosphorus in the soil samples was extracted with 0.5 M $NaHCO_3$ solution at a nearly constant pH of 8.5 following the method described by [33] Watanabe and Olsen (1965). A spectrophotometer was used to measure the intensity of the color developed by the ascorbic acid method, as outlined by [34].
6. Exchangeable K, Ca and Mg	Ammonium acetate extraction method [35]. Extracted by repeated shaking and centrifugation of the soil with a neutral 1 M NH_4OAc solution followed by decantation. The K concentrations in the extract by Knudsen et al. [36]. Ca and Mg concentration by Page et al. [28].
7. Available S	Extracted using 0.15% $CaCl_2$ solution and determined turbidimetrically using $BaCl_2$ crystals [37].
8. Available B	Calcium chloride extraction method [28]. Extracted using hot water–0.02 M $CaCl_2$ solution (1:2) and determined by spectrophotometer following azomethine-H method [38].
9. Available Zn	DTPA extraction method [39].

2.4. Modeling of N Mineralisation

N mineralisation fitted well in the first-order kinetic model. The first-order model is the most commonly used model for understanding the nitrogen dynamics and release pattern from organic compost in soil [40–42]. This can be written in its integrated form as

$$C(t) = CAf\ \{1 - \exp(-Kft)\} \quad (1)$$

where C(t) is the cumulative amount of N mineralised at time t, CAf is the amount of mineralisable N, and the proportionality factor Kf is the mineralisation rate constant of CAf.

2.5. Statistical Analysis

To investigate the treatment impacts, N mineralisation data from various time intervals were fitted to line graphs with their standard error values. Tukey's honestly significant difference test was used to statistically compare the means with a 0.05 probability. For model fitting and statistical analysis, SPSS Inc. software was utilised [7].

3. Results

3.1. Effect of Temperatures on N-Release Pattern from Organic Manures

Soil treated with organic manures significantly released available N (NH_4-N and NO_3-N) throughout 330 days of incubation. Organic manure-amended soil had significantly higher available N content than control soil (Figure 1A–C). Among the organic manures, the PM had the highest available N content, while RSC had the lowest content throughout the incubation period at all three temperature regimes (Figure 1). At all temperatures, PM,

VC, BS and CD showed the highest level of available N in the soil at 60, 45, and 30 days, respectively. On the other hand, WHC and RSC reached their respective peaks at 90 days for 25 °C and 60 days for 35 °C temperature. The highest available N content was found from PM as 222, 239, and 259 μg g^{-1} soil at 15 °C, 25 °C and 35 °C, respectively, which was significantly higher over all other treatments. The level of N in PM, VC, BS and CD-treated soil increased from the initial level (50 μg g^{-1}) throughout the incubation period showing no immobilisation irrespective of temperature regime. But at 25 °C, the N was immobilised for up to 20 days for WHC and RSC. At 35 °C, immobilisation was seen only for RSC for up to 5 days. Thereafter, the release of N was spontaneous in all cases. Available N in control soil did not change significantly throughout the study period and temperature regimes. The N release at 35 °C was approximately 6.1% higher than at 25 °C and 11.2% higher than at 15 °C. Additionally, the N release at 25 °C was 4.7% higher than at 15 °C. At 35 °C, PM released significantly more N than the other manure types: 25.7% more than VC, 59.9% more than BS, 90.4% more than CD, 225.3% more than WHC, and 264.8% more than RSC.

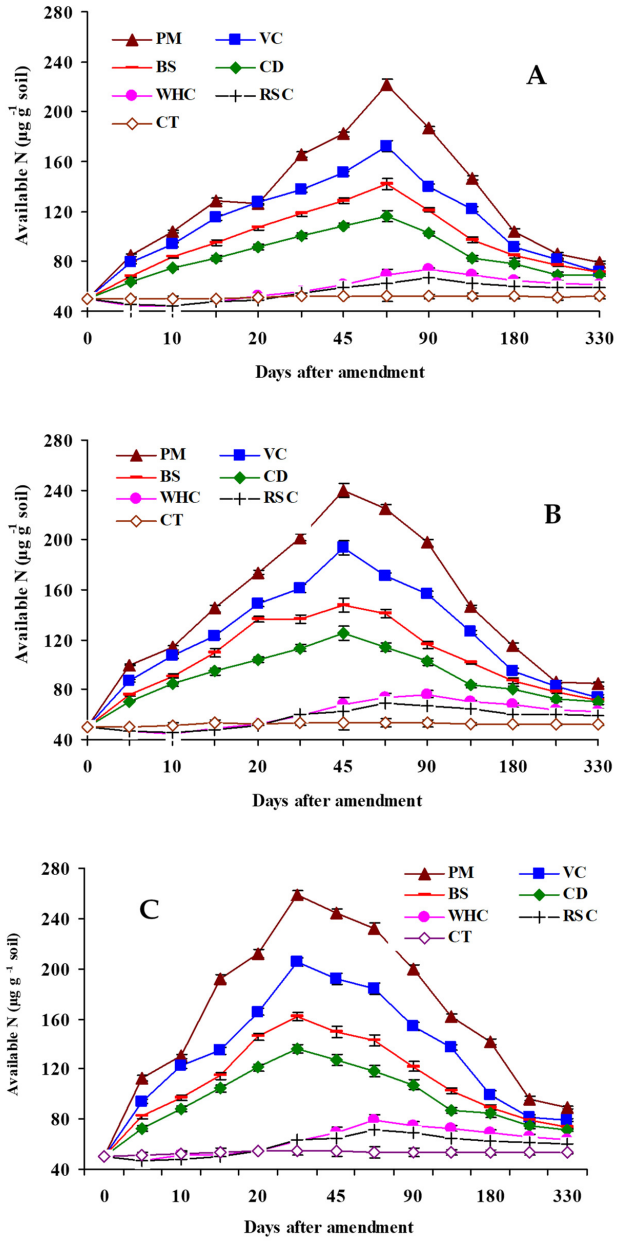


Figure 1. Nitrogen-release patterns from organic manures at 15 °C (**A**), 25 °C (**B**) and 35 °C (**C**) temperatures, bars indicate a standard error at 0.05 probability.

3.1.1. Poultry Manure

Available N-release patterns from PM under 15, 25, and 35 °C varied significantly ($p < 0.05$) due to variations in temperature regimes irrespective of sampling days (Figure 2A). Soil treated with PM incubated under 35 °C had the highest release of N during 330 days of the study period. The second-highest total N release was recorded at 25 °C incubation. The lowest total N was released at 15 °C at all sampling dates. After 30 days of incubation, N release reached a peak under a 35 °C temperature regime. Under the 25 °C temperature regime, the highest point of N release was found at 45 days. However, under 15 °C incubation, the peak was found at 60 days. The corresponding values of total N at peaks were 259, 244, and 233 µg g^{-1} soil at 35, 25, and 15 °C temperature regimes. After reaching peaks, N release decreased gradually, irrespective of temperature regimes.

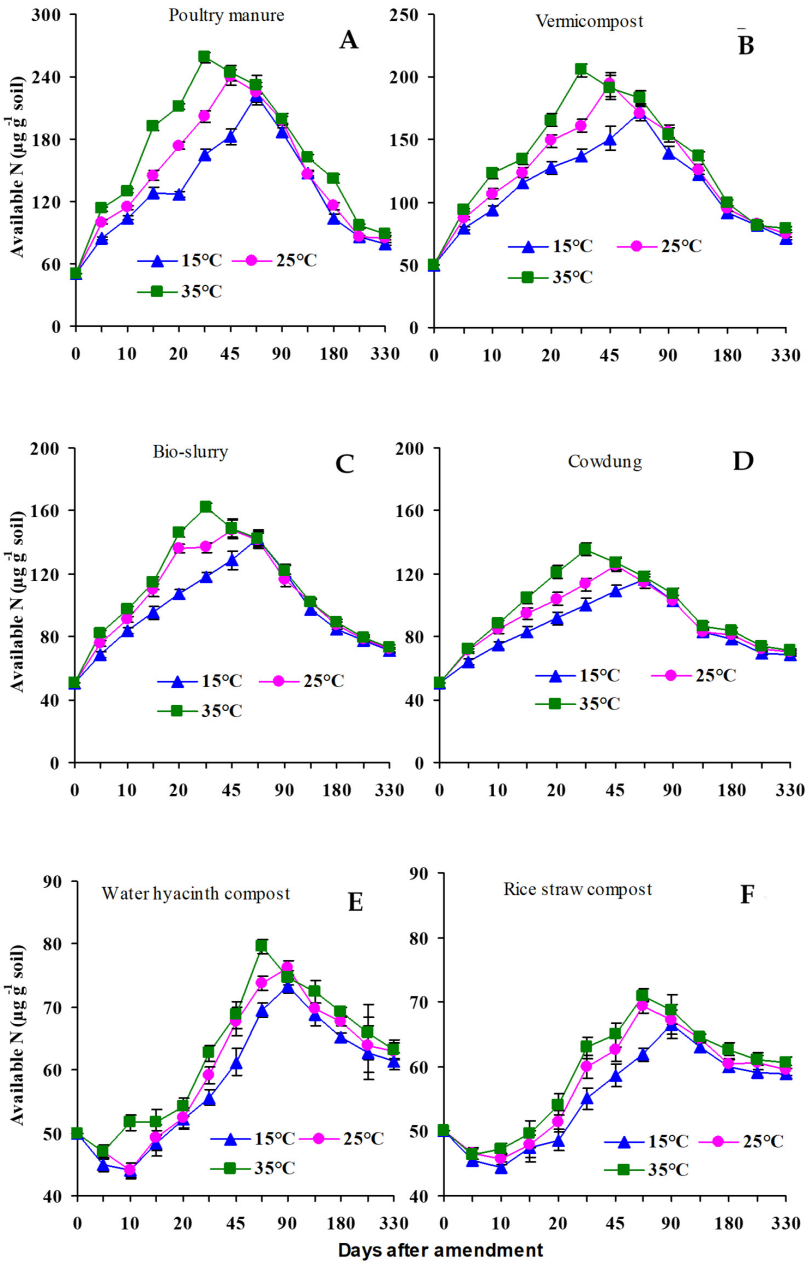


Figure 2. Nitrogen-release pattern from poultry manure (**A**), Vermicompost (**B**), Bio-slurry (**C**), Cowdung (**D**), Water hyacinth compost (**E**) and Rice straw compost (**F**) at 15, 25, and 35 °C temperatures, bars indicate a standard error at 0.05 probability.

At peak under 25 °C, PM released significantly more N than the other manure types: 25.7% more than VC, 59.9% more than BS, 90.4% more than CD, 225.3% more than WHC, and 264.8% more than RSC. At the peak of N mineralisation at 25 °C, PM released 33.3% more N than VC, 67.1% more than BS, 92.1% more than CD, 264.2% more than WHC, and 313.6% more than RSC.

3.1.2. Vermicompost

The release of N from VC was also significantly influenced by temperature regimes where the highest result was obtained from the highest temperature, i.e., the N content increased with the increase in incubation temperature following the order of 35 °C > 25 °C > 15 °C throughout the study period (Figure 2B). N release peaked at 30 days of incubation under 35 °C temperature regimes. At the 25 °C temperature regime, the highest point of N release was found at 45 days, while when the soil was incubated under 15 °C, the peak was found at 60 days of incubation. The releases of total N at peaks were 206, 194, and 172 μg g^{-1} soil at 35, 25, and 15 °C, respectively. After reaching peaks, releases of total N gradually decreased, irrespective of temperature regimes. At final sampling (330 days), the VC-treated soil released 79.2 μg g^{-1} N at best as against 50 μg g^{-1} from the initial soil, indicating that the mineralisation was approaching the finishing touch after gaining momentum with peak (Figure 2B).

3.1.3. Bio-Slurry

BS-amended soil incubated at 35 °C had the peak point 30 and 15 days earlier than at 15 and 25 °C, respectively. Total N release peaked at 30 days of incubation under 35 °C temperature. At 25 °C temperature, the peak N release was found at 45 days, while when soil incubated under 15 °C, the peak was found at 60 days of incubation. Total N at peaks was 162, 148, and 142 μg g^{-1} soil at 35, 25, and 15 °C, respectively. After reaching peaks, releases of N gradually decreased with the progress of the incubation period for three temperature regimes as well. For final sampling taken at 330 days of incubation, only 73.3 μg g^{-1} N was found to be released from BS-treated soil.

3.1.4. Cowdung

The maximum available N (136 μg g^{-1} soil) from CD amended soil was released at 30 days of incubation under 35 °C temperature. At 25 °C temperature, the highest point of N release (126 μg g^{-1} soil) was found at 45 days, while under 15 °C, the peak (116 μg N g^{-1} soil) was found at 60 days of incubation. At final sampling (330 days), 71.1 μg N g^{-1} soil was found for CD amendment as against 50 μg N g^{-1} soil at the initial level (Figure 2D). The trend of fluctuation of mineralisation throughout the study period was almost similar to the other manures mentioned above, irrespective of temperature regimes.

3.1.5. Water Hyacinth Compost

At 35 °C, the release of N was always higher throughout the incubation period, though, during the early 10 days of incubation, the availability of N was reduced in comparison to the initial soil might be due to immobilisation owing to the higher C:N ratio of water hyacinth compost. N released at 25 °C and 15 °C was lower than the N released at 35 °C, and during the initial 20 days of incubation, N was immobilised. For 35 °C, N release reached the peak (79.6 μg g^{-1} soil) at 60 days after incubation, which was much lower than PM, VC and BS. At 15 and 25 °C, the highest points were recorded at 90 days of incubation, showing 73.3 and 76.3 μg N g^{-1} soil, respectively. At the end (330 days after incubation), 63.3 μg N g^{-1} soil was found from WHC, indicating a relatively higher sustenance rate of N than PM-, VC-, and BS-treated soil resulting from slower mineralisation.

3.1.6. Rice Straw Compost

The mineralisation of N from RSC varied significantly ($p < 0.05$) due to different temperature regimes along the sampling period, where the highest result was obtained at

35 °C followed by 25 °C (Figure 2F). At the initial stage of incubation (up to 20 days), the N was, in fact, immobilised, which might be due to a higher C:N ratio in the rice straw compost and thus, the N content went down to the initial level. However, the N content reached the peak (71 and 69.3 μg g^{-1} soil for 35 and 25 °C, respectively) at 60 days of incubation. But at 15 °C, the highest N (66.6 μg g^{-1} soil) content was found at 90 days of incubation, indicating slower mineralisation at lower temperatures. At the end of the study, RSC amended soil retained (59.0–60.6 μg N g^{-1} soil) as compared to 50 μg N g^{-1} soil at the initial level. Although the quantity of N at the end of the study period appeared to be low in RSC-amended soil, the rate of retention was higher owing to low N content in RSC and its slower mineralisation for a wider C:N ratio (Figure 2F).

3.2. Prediction of N Mineralisation Using First-Order Kinetic Model

Cumulative N-mineralisation in soil treated with organic manures and temperature regimes showed different courses along their way of progress; that is, most of the soils with organic manures except RSC and WHC exhibited an exponential course up to a certain period. Table 5 shows measured-N mineralisation as a function of incubation time and fits the single first-order kinetic model for different manures applied in the soil. The R^2 values were generally all close to 1, and standard deviations were low, showing that the selected model could describe the mineralisation process satisfactorily. The cumulative N mineralisation was found to be influenced by different organic manures and temperatures. Parameters of single first-order kinetic models fitted to these mineralisation data are given in Table 5. Two parameters were estimated, namely CAf (easily mineralisable N pool expressed in percentage) and Kf (mineralisation rate constant of the easily degradable N pool).

Table 5. Estimated parameters of a fitted first-order kinetic model for predicting N mineralisation (Values in parentheses are standard deviation).

Treatments	CAf (%)	Kf (%)	R^2
PM × 15 °C	33.3 (0.60)	0.044 (0.002)	0.930
PM × 25 °C	36.9 (0.53)	0.061 (0.001)	0.935
PM × 35 °C	39.3 (0.58)	0.089 (0.000)	0.905
VC × 15 °C	27.3 (0.11)	0.064 (0.001)	0.875
VC × 25 °C	32.1 (0.41)	0.071 (0.001)	0.825
VC × 35 °C	34.3 (0.39)	0.089 (0.000)	0.820
BS × 15 °C	27.2 (0.42)	0.057 (0.001)	0.945
BS × 25 °C	28.7 (0.26)	0.088 (0.001)	0.885
BS × 35 °C	31.0 (0.25)	0.097 (0.001)	0.845
CD × 15 °C	22.1 (0.21)	0.058 (0.001)	0.945
CD × 25 °C	23.5 (0.15)	0.086 (0.002)	0.915
CD × 35 °C	26.4 (0.28)	0.100 (0.003)	0.870
WHC × 15 °C	12.5 (0.87)	0.050 (0.002)	0.860
WHC × 25 °C	16.5 (0.27)	0.060 (0.004)	0.855
WHC × 35 °C	19.1 (0.54)	0.080 (0.001)	0.870
RSC × 15 °C	10.4 (0.35)	0.060 (0.001)	0.945
RSC × 25 °C	15.6 (0.23)	0.080 (0.002)	0.910
RSC × 35 °C	19.9 (0.63)	0.090 (0.002)	0.885
SE (±)	1.19	0.003	0.02
Significance	**	**	*

**, * Significant at $p \leq 0.01$ and $p \leq 0.05$, respectively.

3.3. Easily Mineralisable N Pool (CAf)

Easily mineralisable N pool (CAf) was significantly influenced by manure application and temperature regimes. The interaction effects of manures and temperatures on CAf were significant. The range of easily mineralisable N pools under three temperature regimes was 10.4% to 39.3%, of which the highest mineralisable N was recorded with PM at 35 °C temperature and the lowest in RSC at 15 °C (Table 5). The temperature regime, 35 °C, gave

the highest mineralisable N portion, followed by 25 °C, while the lowest CAf was found at a temperature of 15 °C. Among the manure-treated soils, soil with PM had the highest CAf, followed by soil with VC. The highest result was obtained with soil treated with PM, and the lowest CAf was found with soil treated with RSC (Figure 3). The second highest CAf was recorded in VC under 35 °C temperature. The easily mineralisable N followed the order: PM > VC > BS > CD > WHC > RSC. The CAf at 35 °C was also highest for PM at 39.3%, followed by VC: 34.3%, BS: 31.0%, CD: 26.4%, WHC: 19.1% and RSC: 19.9%. At 35 °C, compared to VC, PM had a 14.6% higher CAf. PM also exhibited a 26.8% higher pool (CAf) than BS, 48.9% higher than CD, 105.8% higher than WHC, and 97.5% higher than RSC.

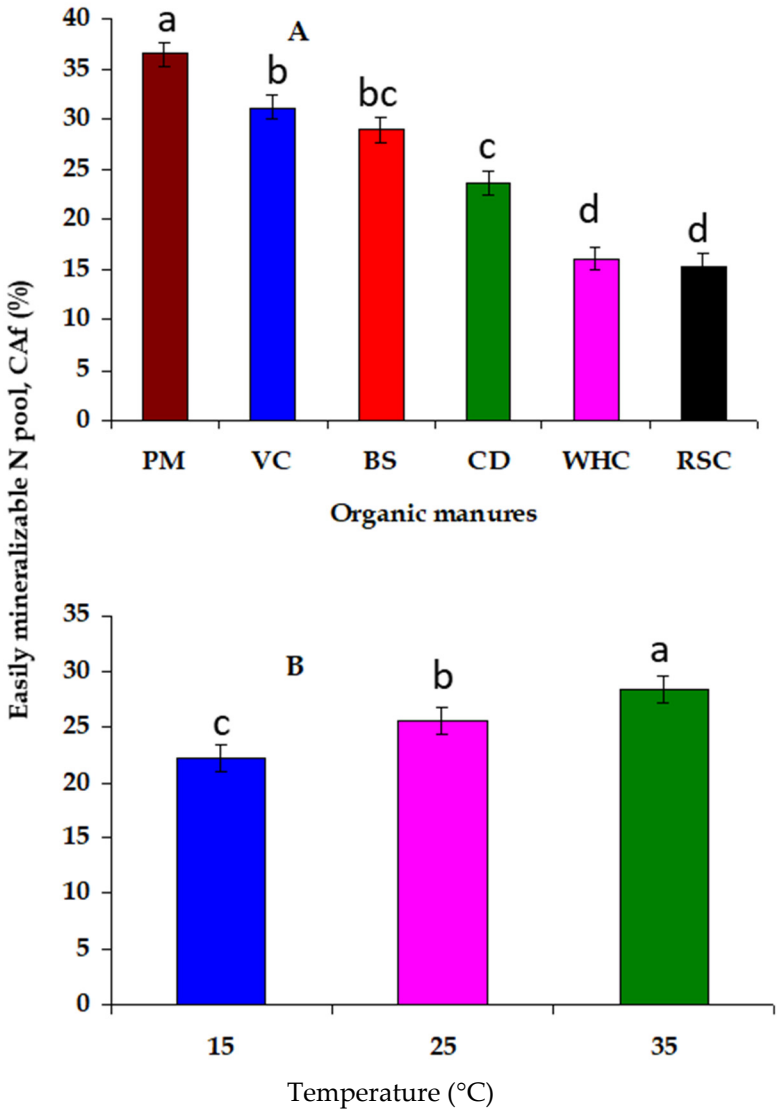


Figure 3. Easily mineralisable N pool (CAf) as influenced by different manures (**A**) and temperatures (**B**). Bars indicate standard error. Different letters above the bars indicate significant differences at 0.05 probability with Tukey's honestly significant difference test. Here, Poultry manure, PM; Vermicompost, VC; Bio-slurry, BS; Cowdung, CD; Water hyacinth compost, WHC and Rice straw compost, RSC.

On the other hand, for the CAf at 25 °C, compared to VC, PM had a 15.4% higher CAf. PM also exhibited a 29.8% higher pool than BS, 43.8% higher than CD, 92.8% higher than WHC, and 113.2% higher than RSC.

3.4. Nitrogen Mineralisation Rate Constant for Easily Mineralisable N Pool (Kf)

The N mineralisation rate constant for easily degradable N pool (Kf) was significantly influenced by manure application and different temperature levels. The values of the mineralisation rate constant of easily degradable N pool (Kf) had a wide range, from 0.044 to 0.10% (Table 5). Among temperature and manure-treated soil, CD-treated soil incubated at 35 °C had the highest Kf value, whereas PM at 15 °C temperature had the lowest value. Among the manure types, the ranges were narrow but still significantly different ($p > 0.05$); the range was 0.063% to 0.082%. CD-added soil had the highest Kf, which was 0.082%, whereas the lowest mineralisation rate constant of easily degraded N pool (0.063%) was recorded in WHC-amended soils. The second-highest Kf was recorded from BS (0.081%). The Kf followed the order: CD > BS > RSC > VC > PM > WHC. Among different temperature regimes, incubation at 35 °C had the highest Kf value (0.091%) and followed the order: 35 °C > 25 °C > 15 °C (Figure 4). The Kf at 35 °C was highest in cowdung (CD) at 0.100%, followed by BS: 0.097%, RSC: 0.090%, VC: 0.089%, PM: 0.089%, and WHC: 0.080%.

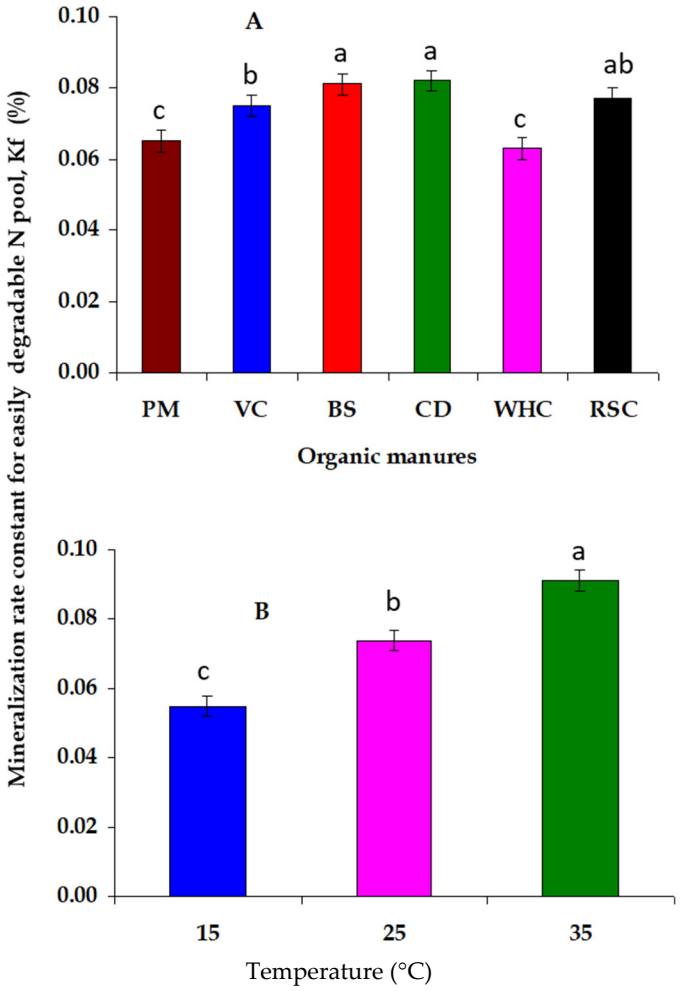


Figure 4. Annual N mineralisation rate (%) influenced by different manures (**A**) and temperature regimes (**B**). Bars indicate standard error. Different letters above the bars indicate significant differences at 0.05 probability with Tukey's honestly significant difference test. Here, Poultry manure, PM; Vermicompost, VC; Bio-slurry, BS; Cowdung, CD; Water hyacinth compost, WHC and Rice straw compost, RSC.

At 35 °C, CD had a 3.1% higher Kf than BS, 11.1% higher than RSC, and 12.4% higher than both VC and PM. The Kf for CD was 25.0% higher than for WHC.

At 25 °C, the Kf of CD was 3.7% higher than BS, 13.5% higher than VC, 16.7% higher than RSC, 20.0% higher than PM, and 37.7% higher than WHC.

4. Discussion

4.1. Effect of Temperature Regimes and Different Organic Manures on N-Release Patterns

The N dynamics pattern of some selected manures at different temperature regimes in the current study suggested that the N availability of crops from applied manures greatly depends on the types of manures and prevalent temperature.

The decrease in available N can be attributed to the utilisation of N by increasing microbial population and simultaneous loss through denitrification [43–46]. In the later days, the rate of denitrification exceeds the rate of mineralisation of organic N and thus results in its lower value [47–49]. Asagi and Ueno [50], Hlaing et al. [51], and Ishikawa [52] reported that N mineralisation of green manure (GM) in paddy soils reached its peak within 4 to 6 weeks at 23 to 30 °C. Asagi and Ueno [50] found that N mineralisation of various 15N-labeled green manures in paddy soils peaked within 4 to 6 weeks at temperatures ranging from 23 to 30 °C, highlighting the critical role of temperature in accelerating microbial activity. Similarly, Hlaing et al. [51] demonstrated that green manure crops significantly enhanced mineralisable N in paddy soils under similar temperature conditions, corroborating the influence of warm temperatures on N release. Ishikawa [52] further supported these findings by detailing how green manure applications in Japanese rice farming systems optimised N availability during the critical early weeks of decomposition. These studies align with the present research, which also underscores the substantial effect of temperature on N mineralisation rates, particularly in the context of organic manure use in subtropical conditions.

There was no mineralisable N in RSC-treated soils, particularly for up to 20 days of incubation, which indicates that the N released from RSC-amended soils was almost fully immobilised by the microbes in up to 20 days at 15, 25, and 35 °C (Figure 1). The mineralisation and immobilisation of N were highly related to the C:N ratio in the soils [53]. Higher mineralisation occurred at a narrower C:N ratio, and the reverse happened for N immobilization [53]. The C:N ratios in the PM, VC, BS, CD, WHC, and RSC amended soils at the start of incubation were 10.8, 14.7, 20.0, 25.8, 50.0, and 70.0, respectively (Tables 1 and 2). The N-release from added manures was negatively related to the C:N ratio. Black [54] reported that in many cases, the critical C:N ratio for N mineralisation and immobilisation fell between 15 and 33, which in the present study value was found to be 50 and 70 for WHC and RSC, respectively.

The mineralisation–immobilisation process normally depends on the C:N ratios of the added organic manures [55]. A negative relationship between N-mineralisation and C:N ratios of the added organic manure under the aerobic and anaerobic conditions of soil was reported by many investigators [56–58]. The lower C:N ratio in PM, VC, BS, and CD (10.8, 14.7, 20.0, and 25.8, respectively) induced more mineralisation than immobilisation (Tables 1 and 2). The lower C:N ratio in decomposed PM, VC, BS and CD induced mineralisation throughout the incubation period. On the other hand, the highest C:N ratio (70) in RSC and WHC (50) induced mineralisation for up to 49 days of the incubation period. There was practically no N mineralisation from WHC and RSC during the first 20 days of incubation after adding them, but thereafter, N mineralisation proceeded to follow the pattern of other manures. Similar results were found by Mishra et al. [59].

After the application of organic manure in the soil, the readily decomposable nitrogenous substances were mineralised first [7]. A portion of mineralised N was absorbed rapidly into the microbial body, and the rest of N was released in the soil as available N. The amount of this available N would be higher if the soil is amended with organic manure of lower C:N ratios or higher N content. Moreover, if the added organic manure has high C:N ratios or low N content, such as WHC and RSC, the mineralised N would be immobilised immediately after the decomposition. Behind this phenomenon, the probable fact is that the rapid decomposition of added C at the initial stage of incubation increases the N demand

for microbial biomass to their metabolic activities, and thus, initially, the available N in the soil became unavailable due to immobilisation. The free-living microorganisms that take up N in their life eventually release it into the soil after their death.

4.2. Predicting N Mineralisation Using First-Order Kinetic Models

Mineralised N in soil from organic sources contributes to soil fertility and crop productivity. To understand the release pattern of N by employing the kinetic model, the incubation data were run into the first-order kinetic model to estimate the easily mineralisable N pool (CAf) and the mineralisation rate constant (Kf) (Table 5, Figures 3 and 4). The output of the model reveals that the parameters varied due to the manure type and the incubation temperature.

4.2.1. CAf

The incubation research showed that the greatest CAf was observed with PM at a temperature regime of 35 °C, reaching 39.3%, whereas the minimal CAf was noted in RSC under the 15 °C regime, registering at 10.4% (Table 5 and Figure 3). A clear positive relationship between higher temperatures and increased CAf suggests that elevated temperatures boost microbial activity and N mineralisation rates, corroborating other scholarly works that link enhanced mineralisation to stimulated microbial metabolism and enzymatic activities in warmer conditions [60–62].

Additionally, our findings indicate a significant impact of manure types on CAf. Soils amended with PM consistently presented the highest CAf values (36.5%), outperforming those treated with VC. On the contrary, RSC-applied soils manifested the lowest CAf levels. Precisely, PM amendments resulted in CAf being 5.28%, 7.52%, 12.9%, 20.5%, and 21.2% greater relative to VC, BS, CD, WHC, and RSC, respectively. This trend highlights the superior N release potential of PM, making it the most effective organic manure for maximising N availability under varying temperature conditions. The consistent performance of PM, followed by VC, underscores the importance of manure selection in achieving optimal N mineralisation, particularly in warmer climates.

The higher values of CAf recorded with PM and VC might have resulted from increased nutrient content and higher decomposition rate, as confirmed by studies pointing out that PM and VC intensify nutrient availability in the soil more effectively than other organic materials used in the study [63].

Chadwick et al. [64] also reported variability in mineralisable N in organic manure used as a N source. However, Indraratne et al. [65] reported that the current guidelines for applying manure as a source of N often take a one-size-fits-all approach, ignoring the significant variability in manure quality from even the same species [64]. This oversight disregards key factors and results in inaccurate predictions of plant-available N. Stanford and Smith [66] and Alvarez and Alvarez [67] conducted research into the decomposition kinetics assuming that organic-N breaks down at a first-order rate, a pattern commonly seen in the decay of organic materials, while variable mineralisable N pool is reported in different organic manures during decomposition.

The study of Azeez and Averbeke [68], Stanford and Smith [66], and Alvarez and Alvarez [67] identified distinct stages in the N-release pattern: a rapid initial release during the first 30 days, followed by consistent releasing from day 40 to 55, a marked decrease between days 70 and 90, and then a significant rise at day 120, likely due to the breakdown of microbial cells. It suggests that if nitrate is not captured by microbes or absorbed by crops within the initial 30 days, it is likely to be lost through leaching. Therefore, timing the crop absorption with periods of high N availability from manures/composts is crucial [68].

However, Moharana and Biswas [69] suggest that field studies conducted in the actual environment on PMN fraction and its changes during the crop's growth could provide more useful information than common incubation studies for assessing how organic fertilisers release mineral N.

4.2.2. Kf

The variation in Kf values observed across different manure types and temperature regimes highlights the significant impact of these factors on N mineralisation rates. Notably, CD incubated at 35 °C exhibited the highest Kf value (0.1), suggesting a rapid rate of N mineralisation under warmer conditions. In contrast, PM incubated at 15 °C demonstrated the lowest Kf value (0.044), indicating a slower mineralisation process at lower temperatures (Table 5, Figure 4).

These findings suggest that despite having a lower CAf), CD decomposes more efficiently at higher temperatures compared to other manures. This accelerated decomposition could be attributed to the increased microbial activity and enhanced enzymatic processes at elevated temperatures, which facilitate faster nutrient release from CD.

The order of Kf values, with CD > BS > RSC > VC > PM > WHC, further emphasizes the differential responses of organic manures to temperature variations. This hierarchy underscores the importance of selecting the appropriate manure type based on the prevailing temperature conditions to optimise N availability for crops.

These findings confirm the research works of others who have exhibited that the chemical composition of organic materials and prevailing environmental conditions cause varying decomposition rates of organic materials [7,70,71].

4.2.3. Model Fitness

The first-order kinetic model provided an excellent fit for the N mineralisation data across all treatments, evidenced by high R^2 values close to 1 and low standard error estimates. This demonstrates the model's robustness in describing N mineralisation dynamics, consistent with literature where first-order models have effectively predicted N release from organic amendments under diverse conditions [7,72,73].

5. Conclusions

Different organic manures have varied N-release patterns under different thermal regimes. After reaching its peak, N release decreased and reached a steady state across all temperature ranges. Soils treated with poultry manure and vermicompost had the highest total N released throughout the incubation study period, followed by bio-slurry, cowdung compost, water hyacinth compost, and rice straw compost. The first-order kinetic model could satisfactorily describe N release from organic manures. Considering overall performance, poultry manure and vermicompost could be regarded as the best source of organic materials, followed by bio-slurry for their nutrient-releasing ability, production sustainability, economic viability and maintenance of soil fertility. For optimal N access, farmers in warm regions or high-growth periods should prefer poultry manure due to its superior mineralisation at higher temperatures. Agricultural directives need to advocate for using poultry manure or vermicompost in subtropical areas, as it offers better N accessibility compared to other organic fertilisers. Long-term studies, including field-level studies, should be conducted to validate the findings of the present study. The advantageous use of particular organic manures across varying temperature conditions should be highlighted to boost crop yields and decrease reliance on synthetic fertilisers.

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