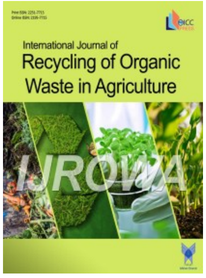

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Research Article

Nutrient Release Pattern of Different Organic Sources under Controlled Conditions

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Abstract

Purpose: It is essential to have up-to-date knowledge about the mineralization of organic sources and the release patterns of nutrients to ensure that crops receive sufficient nutrients throughout their growth cycle. Organic sources like compost, animal manure, and green manure are valuable nutrient sources for crop production. However, the nutrient content of these sources can vary based on factors such as the source, composition, and processing method. This study aimed to determine the release patterns of nitrogen (N), phosphorus (P), and potassium (K) from various organic sources to optimize their utilization.
Method: Seven types of compost, EPMC, CPM, GMI, Kitchen Organic Waste Compost (KOWC), Biochar-Enriched Compost (BEC), CWS, and Value-Added Compost (VAC), were collected from organic sources and evaluated for nutrient release patterns under controlled conditions over a 60-day period.
Results: The variations in SOM, C dynamics, nutrient mineralization rate were associated with chemical composition of the manures. EPMC was found as the most suitable P organic amendment for integration with chemical N fertilizers while KOWC demonstrated superior potential as an P organic source and BEC as a K-rich organic amendment. Additionally, VAC exhibited the most balanced and consistent nutrient release characteristics, making it a strong candidate for use as a general-purpose organic nutrient source.
Conclusion: No single manure type can be universally recommended for integrated management of N, P and K. Instead, nutrient specific calibration and detailed characterization of each manure source are essential for optimize the combined use of organic and inorganic nutrient inputs.

Keywords: Composting, Compost value addition, Organic sources, Nutrient pattern

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1. Introduction

The decline in soil fertility is a global issue affecting crop yields, especially in countries like Pakistan where agriculture plays a crucial role in the economy (ur Rehman et al., 2021). Factors contributing to this decline include increased cropping intensity, the use of high-yielding varieties, nutrient loss due to abiotic factors, and improper application of N, P, and K fertilizers without adequate use of organic manures. In Pakistan, organic manure usage is limited, with most farmers relying on chemical fertilizers, leading to a depletion of soil organic matter (SOM) and soil health degradation. However, incorporating organic sources like compost, farmyard manure (FYM), and poultry manure (PM) can restore soil fertility, enhance crop productivity, and mitigate environmental impacts.

Improper disposal of organic waste poses environmental hazards, impacting aesthetics, human health, and greenhouse gas emissions (Polprasert, 2007, Lee et al., 2020). The Environmental Protection Agency (EPA) reports a significant annual solid waste production in Pakistan, with a substantial portion being food waste (Sharma et al., 2020). Utilizing organic manures may not provide immediate crop nutrition benefits but has long-term positive effects on soil health. Pakistan's growing poultry industry generates substantial organic waste, which can be converted into organic fertilizers through composting (Joshi et al., 2020; Ahmed et al., 2021). Similarly, the increasing livestock population in the country produces a significant amount of manure, with potential for utilizing these organic wastes to meet crop nutrient requirements (FAOSTAT, 2019). Press mud, a byproduct, has been shown to improve nutrient uptake, yield, and growth when combined with chemical fertilizers (Diaz, 2016). Asghar & Afzal (2020), Budiyanto (2021), Gunjal & Gunjal (2021) have reported up to a 20% increase in nutrient uptake and up to a 10% increase in yield due to the combined application of press mud and chemical fertilizers. Green manuring, incorporating green crop residues into the soil, enhances soil organic matter content and fertility (Li et al., 2020; Iderawumi & Kamal, 2022).

Biochar, as a compost additive, improves composting efficiency, microbial activity, and reduces greenhouse gas emissions (Wang et al., 2020). Combining compost and biochar applications in soil benefits plant growth and soil health, enhancing nutrient use efficiency, yield, and crop quality (Guo et al., 2020).

As farmers face stagnant crop yields despite continuous chemical fertilizer application, there is a growing interest in alternative soil fertility management practices (Zhang et al., 2013). Reviving traditional agricultural inputs and integrating chemical fertilizers with organic sources can help maintain soil fertility and productivity. Understanding mineralization rates and nutrient release patterns of organic sources is crucial for optimizing application rates and timing to support crop growth and yield throughout the growing season.

2. Materials and methods

2.1. Experimental details

An incubation study was conducted in the research laboratory of the Department of Soil and Environmental Sciences at MNSUA, Multan, Pakistan. The study aimed to identify promising organic sources for future experimentation based on their nutrient release patterns and other physical characteristics. Details are presented in Table 1.

Table 1. Pre-incubation characteristics of the organic manures utilized in the study

Manure Characteristics	Organic manures						
	FYM	EPMC	CPM	KOWC	BEC	CWS	VAC
pH	7.30	6.00	6.50	6.63	7.20	6.80	6.30
Organic matter (%)	27.5	60.9	33.6	24.7	76.0	4.3	60.6
Carbon contents (%)	16.0	35.4	19.5	14.4	44.2	2.5	35.2
Total N contents (%)	0.97	1.38	2.1	1.42	0.61	0.79	1.58
Available P (%)	0.06	1.8	0.13	5.29	0.24	0.56	2.56
Available K (%)	0.42	1.60	0.44	1.30	0.70	0.87	1.23
C:N	16.5	25.7	9.30	10.1	72.4	3.16	22.3
C:P	266	19.7	150	2.71	184	4.46	13.8

Note: Farmyard manure (FYM), Enriched Poultry manure compost (EPMC), Composted press mud (CPM), Kitchen organic waste compost (KOWC), Biochar enriched compost (BEC), Composted wheat straw (CWS), and Value-added compost (VAC). It is worth noting that FYM and CWS were included in the study as these manures are conventionally used by farmers in Pakistan.

2.2. Experimental layout

This incubation study was conducted in 2019 using soil media to profile organic manures based on nutrient mineralization rate and other characteristics. The study followed a two-factor completely randomized design (CRD) with three replications. The treatment plan included eight organic sources (Enriched Poultry Manure Compost (EPMC), Composted Press Mud (CPM), Green Manure/Berseem Incorporation (GMI), Kitchen Organic Waste Compost (KOWC), Biochar-Enriched Compost (BEC), Composted Wheat Stubbles (CWS), and Value-Added Compost (VAC)) and one control treatment as Factor A, while five sampling times (3, 15, 30, 45 and 60 DAI) as Factor B. Below are detailed descriptions of both factors for better understanding:

Factor A		Factor B	
Organic manure used	Symbol	Sampling time	Symbol
Farmyard manure	FYM	3 days after incubation	3 DAI
Enriched poultry manure compost	EPMC	15 days after incubation	15 DAI
Composted press mud	CPM	30 days after incubation	30 DAI
Green manure/Berseem incorporation	GMI	45 days after incubation	45 DAI
Kitchen organic waste compost	KOWC	60 days after incubation	60 DAI
Biochar-enriched compost	BEC		
Composted wheat stubbles	CWS		
Value-added compost	VAC		

A control treatment without organic manure was also included. The objective of incorporating FYM in the treatment plan was to compare the effects of prepared composts with those of FYM, as the application of FYM is a common practice among tomato growers. Farmyard manure (FYM) from cows and buffaloes was collected from the surrounding area, dried under shade, ground, and stored at 4°C until use. Berseem (*Trifolium alexandrinum*) grown in nearby fields was collected, chopped, and incorporated into the soil for the green manure incorporation treatment. Kitchen-based organic waste was collected from nearby residential areas, and press mud was obtained from sugarcane juicer shops. Poultry manure was purchased from a nearby poultry shed, and wheat chopped straw was bought from a farmer. For composting, all these materials, including kitchen waste, press mud, poultry manure, and chopped wheat straw, were buried in an earthen pit lined with a polyethylene sheet for 90 days in the Research Block of the university (Figure 1).

Rock-phosphate was added to the pit of poultry manure to produce EPMC. Proper moisture was maintained to keep all the materials wet, while avoiding waterlogging. The materials were turned over two to three times per week. After 90 days, the materials from each pit were collected, shade-dried, ground, and stored at 4°C until use.

The university's lawn development waste was utilized to prepare biochar-enriched compost. Cuttings from lawns, pruned trees, and shrubs were collected and transferred to the University Solid Waste Management site.

These branches were either burnt anaerobically to produce biochar or shredded into small pieces.

The shredded material and biochar were composted to obtain biochar-enriched compost (BEC) using the same procedure as described above. The analysis of the different prepared composts is provided in Table 1. For the preparation of Value-Added Compost (VAC), various ingredients including poultry manure (PM), farmyard manure (FYM), press mud, biochar, peat moss, and rock phosphate were mixed in different ratios and composted at Ambala Agri Tech Industry in Multan (Figure 2). Several grades were tested, and the optimal composition was determined to be 40% PM, 10% FYM, 10% kitchen organic waste, 5% press mud, 15% biochar, 10% peat moss, and 10% rock phosphate. Additionally, a strain of phosphorus-solubilizing bacteria (PSB) obtained from the Soil Microbiology Section of the department was in the mixture.

The characteristics of the final VAC product are outlined in Table 1. The prepared VAC was stored at 4°C until it was ready for application.

Figure 1. Overview of composting process for organic manures

Figure 2. Overview of the preparation of VAC at Ambala Agri Tech Industry, Multan

2.3. Conducting the incubation study

A composite sample of the soil was collected from the experimental area of MNS University of Agriculture, Multan, and analyzed for physiochemical properties (Table 2).

Table 2. Physiochemical characteristics of the experimental soil

Soil Characteristics	Values	Reference
Soil Texture	Silt Loam	Black et al. (1965)
Sand (%)	30.0	
Silt (%)	52.0	
Clay (%)	18.0	
Soil organic matter (%)	0.76	Walkley (1974)
CEC Cmol (-) Kg^{-1}	11.6	Chapman & Pratt (1961)
EC (dS m^{-1})	2.1	
pH	8.2	Jackson (1973)
Total N (%)	0.039	Bremner & Mulvaney (1982)
Available P (mg kg^{-1})	8.6	Olsen (1954)
Exchangeable K (mg kg^{-1})	172.2	Knudsen et al. (1982)

After analysis, the collected soil was dried, milled, and sieved through a 2 mm sieve. It was then used to fill plastic cups at a rate of 1 kg per cup. Organic sources or manure (10 g per kg of soil) were thoroughly mixed into the soil and moistened with distilled water. The moisture content in each cup was maintained at field capacity based on weight. All 135 plastic cups containing treated soil were covered to prevent evaporation losses and incubated at 28±3˚C for 60 days. At 15-day intervals until the end of the 60-day incubation period, one set of cups (27 cups) was removed each time and analyzed for various soil and nutrient characteristics.

Data collection: After 3 days of incubation, one set of cups containing soil mixed with various manures was taken and analyzed. The findings were used as a baseline for determining nutrient release patterns and other characteristics. Using standard protocols or methods (Wolf, 1996; Ryan et al., 2001), data related to SOM, Olsen P, available K, total N, soil pH, soil EC, and microbial count were collected.

Classification of organic manures: Organic manures were classified based on their rate of nutrient release pattern, C:N ratios, and other features using the method described by Gunes et al. (2006) and Hassan et al. (2011).

2.4. Statistical analysis

The data were analysed using ANOVA (Steel et al., 1997) and the means were compared using Tukey's HSD test at $p \leq 0.05$ probability. Graphical presentation of the rate of mineralization and relationships among various factors was done using Microsoft Office software.

3. Results and discussion

3.1. Soil organic matter (SOM) and carbon (%)

After 3 days of incubation, most of the cups had reached moisture levels equivalent to field capacity, establishing this stage as the baseline for soil carbon (C) and other analyses. Results regarding soil C indicate that the effect of all treatments was statistically significant ($p < 0.01$). The data in Table 3 demonstrate that soil C levels varied depending on the type of organic manure used. The application of BEC resulted in the highest soil C content (38.1%), followed by EPMC (17.8%) at 3 days after initial application (DAI), while CWS had the lowest soil C content (1.25%) compared to the control (0.34%). This trend was consistent up to 60 DAI. At 3 DAI, the highest C content in the incubated soil might have occurred due to the higher initial C content in BEC, as shown in Table 1, where BEC contained 44.2% C. In contrast to BEC, CWS exhibited the lowest C mineralization, with only 2.5% C, as it contained the lowest C content among all the composts used (Table 1).

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Comparing different organic manures, BEC and EPMC decomposed more rapidly than VAC and FYM. It can be inferred that organic manures with lower soil C content at various incubation intervals have the potential to retain organic matter for a longer duration compared to those with higher soil C levels (Table 3). Similar trends were observed for SOM. These changes may be attributed to arid to semi-arid climatic conditions. In Pakistan, the arid to semi-arid climate, coupled with an extensive mono-cropping system, accelerates the decomposition of organic matter, leading to rapid mineralization of applied organic manures (ur Rehman et al., 2021).

Therefore, it has become a challenge to accurately estimate the factors influencing organic matter mineralization in soils.

Monitoring nutrient levels in the soil after adding known quantities of organic manure can help assess nutrient release patterns from organic sources.

Table 3. Soil carbon contents (%) at different incubation intervals of organic manures

Organic manure	Incubation time (days)					Mean
	3	15	30	45	60	
Control	0.24 v	0.30 v	0.34 v	0.20 v	0.16 v	0.25 G
FYM	5.49 n-p	6.56 l-n	8.02 jk	4.30 qr	3.40 rs	5.55 D
EPMC	11.97 h	14.19 g	17.75 e	8.62 j	6.63 lm	11.83 B
CPM	6.93 kl	7.95 jk	9.78 i	5.77 m-o	4.73 o-q	7.03 C
GMI	1.01 uv	1.22 uv	1.50 tu	0.84 uv	0.69 uv	1.05 F
KOWC	4.35 qr	5.51 n-p	7.19 kl	3.29 rs	2.37 st	4.54 E
BEC	24.95 c	28.697 b	38.12 a	20.37 d	15.48 f	25.53 A
CWS	0.88 uv	1.07 uv	1.25 t-v	0.70 uv	0.55 uv	0.89 F
VAC	7.20 kl	8.66 j	10.78 i	5.73 m-p	4.64 pq	7.40 C
Mean	7.01 C	8.24 B	10.53 A	5.54 D	4.30 E	

HSD values: Organic manure (A) = , Incubation time (B) =, A×B = 1.1199, CV = 4.71

F-value / Level of significance: A = **, B = **, A×B = **,

Note: Control = soil without manures, ** highly significant, FYM (Farmyard manure), EPMC (Enriched Poultry manure compost), CPM (Composted press mud), GMI (Green manure i.e. berseem incorporated), KOWC (Kitchen organic waste compost), BEC (Biochar enriched compost), CWS (Composted wheat straw), VAC (Value added compost).

3.2. Soil pH, soil EC, and microbial count

Soil pH, soil EC, and microbial count data are presented in Figures 3, 4 and 5 respectively.

These figures illustrate the individual and combined effects of manure type and incubation period on N, P, and K soil contents, which significantly influenced soil pH (Figure 3).

However, the differences among various treatments in terms of changes in soil pH were minimal.

The data on soil pH indicated that soil samples treated with organic manures had lower soil pH compared to the control soil without manure application.

The change in soil pH in organically treated soils may result from the release of organic acids during the decomposition of these organic sources. Similar findings were reported by ur Rehman et al. (2021) for soils treated with organic manures in various forms. Secondly, these changes might be happened because of significant rise in microbial population in the soils and our findings also showed higher microbial population in those soils where compost was used compared to soils of the control treatment. The addition of organic manures had a significant impact on soil EC compared to the control (Figure 4).

When comparing different manures, it was observed that the application of KPMC resulted in the lowest soil pH value, followed by VAC and EPMC. Similarly, the soil EC of these samples was also higher than in some samples without organic matter. This could be attributed to the release of more nutrients during mineralization compared to the control treatments (Figure 4). The results in Figure 5 also showed that the application of organic manures increased the microbial count in treatments where EPCM and VAC with chemical fertilizers were applied compared to the control treatment. These enhancements in microbial count may be due to the increase in soil organic matter (SOM) content, as discussed in Table 4.

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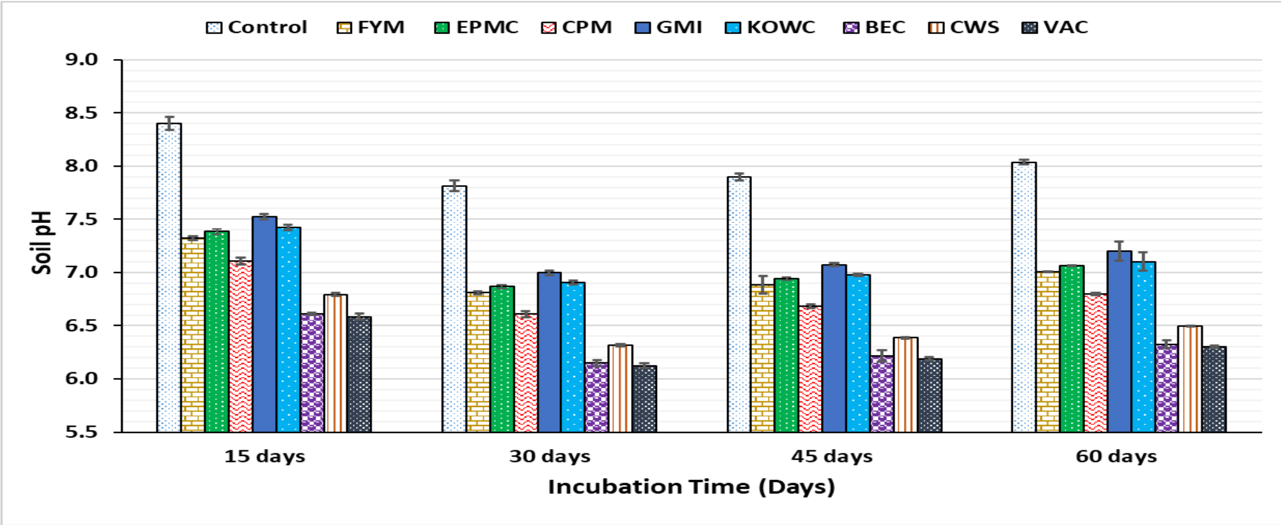

Figure 3. Variations in soil pH due to mineralization of organic manures under controlled conditions [28±3°C, mean effect]

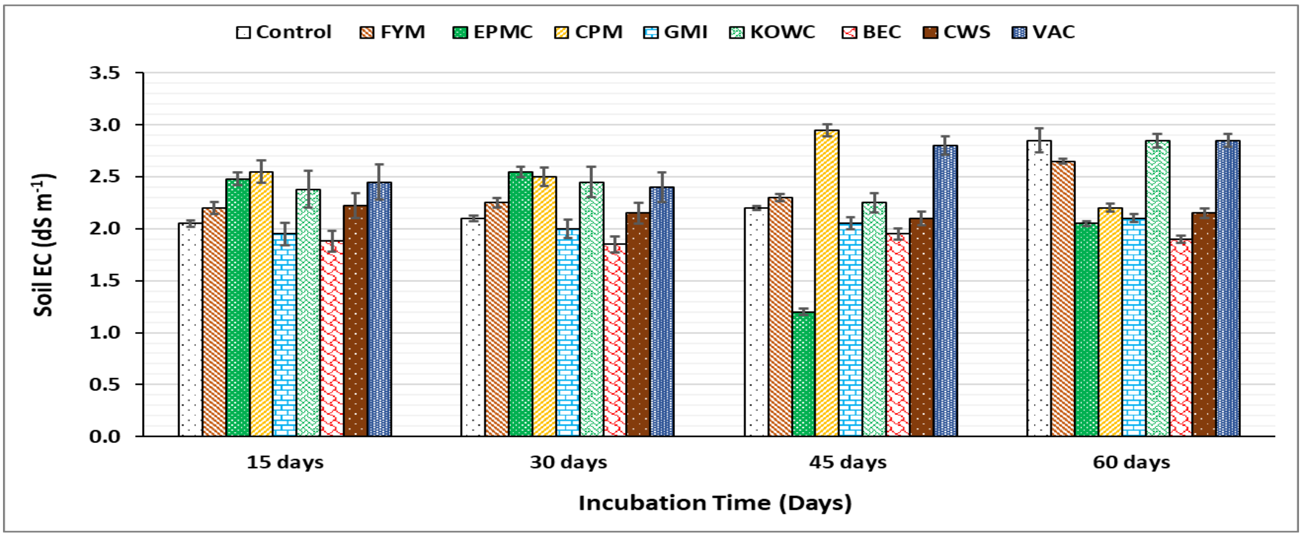

Figure 4. Variations in soil EC (mS cm^{-1}) due to addition organic manures under controlled conditions [28±3°C, mean effect]

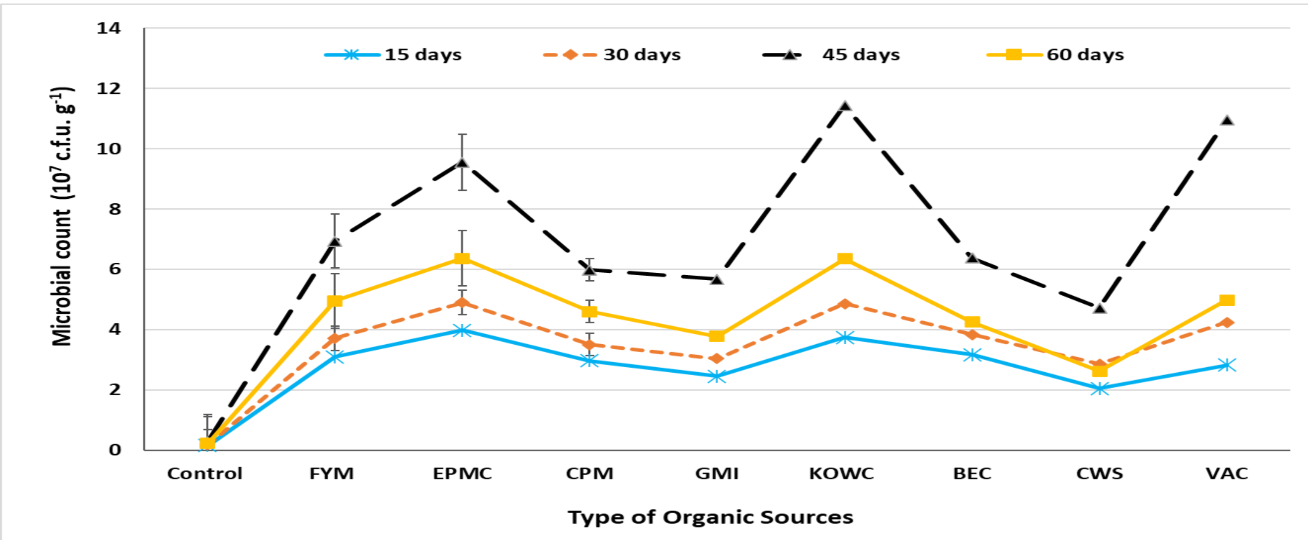

Figure 5. Variations in microbial count (107 c.f.u. g^{-1}) due to addition organic manures under controlled conditions [28±3°C, mean effect]

Whereas: FYM (Farmyard manure), EPMC (Enriched Poultry manure compost), CPM (Composted press mud), GMI (Green manure i.e. berseem incorporated), KOWC (Kitchen organic waste compost), BEC (Biochar enriched compost), CWS (Composted wheat straw), VAC (Value added compost)

* without organic manure

Table 4. Soil organic matter percentage at various incubation intervals

Organic manure	Incubation time (days)					Mean
	3	15	30	45	60	
Control*	9.9 m-o	5.8 rs	0.5 v	7.4 qr	1.8 uv	0.4 G
FYM	8.1 o-q	30.5 e	0.5 v	5.6 rs	1.5 uv	9.5 D
EPMC	2.5 tu	24.4 g	0.4 v	4.0 st	1.2 uv	20.3 B
CPM	2.1 uv	20.6 h	0.3 v	65.5 a	0.9 uv	12.0 C
GMI	1.7 uv	14.8 j	0.2 v	49.3 b	18.5 i	1.8 F
KOWC	1.4 uv	11.4 lm	13.8 jk	42.9 c	14.8 j	7.8 E
BEC	1.1 uv	16.8 i	11.2 l-n	35.0 d	12.3 kl	43.9 A
CWS	12.3 kl	13.6 jk	9.4 n-p	26.6 f	9.8 m-p	1.5 F
VAC	9.4 n-p	11.9 kl	7.4 qr	2.1 t-v	7.9 pq	12.7 C
Mean	12.0 C	14.1 B	18.1 A	9.5 D	7.3 E	

HSD values: Organic manure (A) = 0.3899, Incubation time (B) = 0.2546, A×B = 1.1199, CV = 4.71
F-value / Level of significance: A = **, B = **, A×B = *, Note: Control = soil without manures, * significant, **highly significant, FYM (Farmyard manure), EPMC (Enriched Poultry manure compost), CPM (Composted press mud), GMI (Green manure i.e. berseem incorporated), KOWC (Kitchen organic waste compost), BEC (Biochar enriched compost), CWS (Composted wheat straw), VAC (Value added compost).

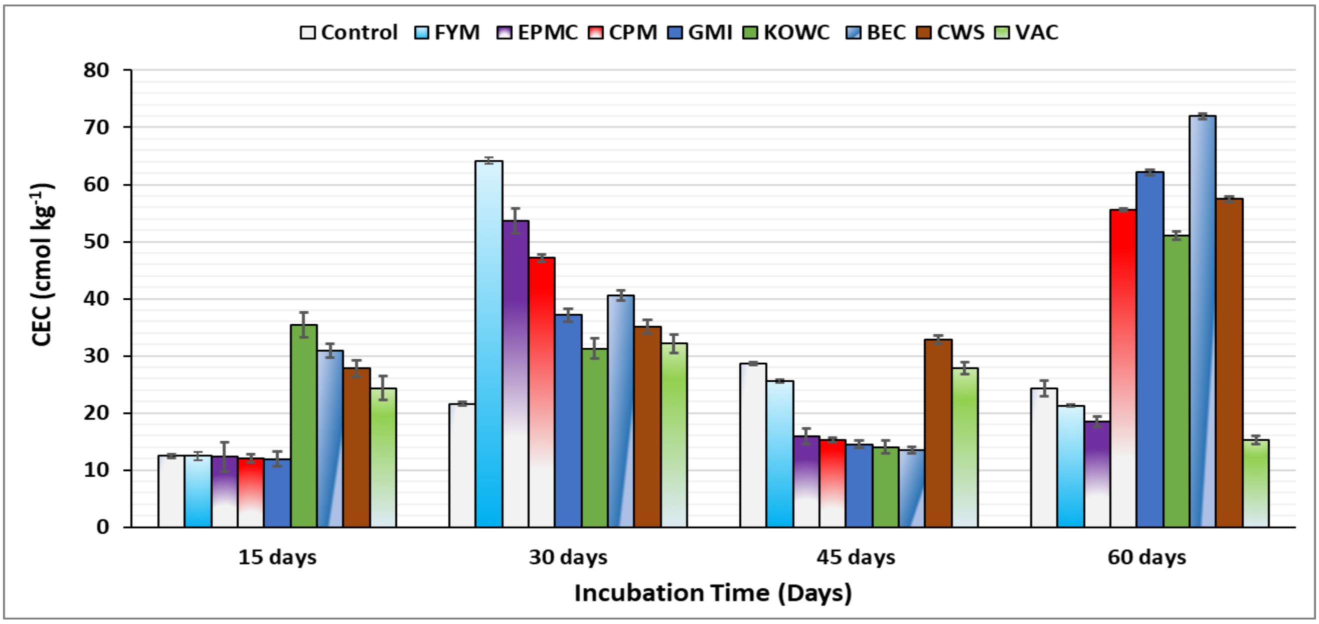

Figure 6. Variations in soil CEC due to addition organic manures under controlled conditions [28±3°C, mean effect].
Whereas: FYM (Farmyard manure), EPMC (Enriched Poultry manure compost), CPM (Composted press mud), GMI (Green manure i.e. berseem incorporated), KOWC (Kitchen organic waste compost), BEC (Biochar enriched compost), CWS (Composted wheat straw), VAC (Value added compost)
* without organic manure

It is documented in the literature that organic manure enriched with organic matter provides a diverse range of nutrients to support the growth of microorganisms, particularly bacteria. It is well reported that aerobic microbes produce more CO_2 which is converted to carbonic acid after reaction with water and thus aerobic microbes results in a significant decline in soil pH. Therefore, the application of KPMC and VAC significantly increased the microbial count. The SOM provides a food source for microorganisms, which ultimately leads to the proliferation of microorganisms. Additionally, organic manures can also help improve soil structure and moisture retention, creating a more favourable environment for microbial growth. Figure 6 also showed significant increase in soil CEC. Since soil CEC is directly associated with soil organic matter contents, treatments with higher soil organic matter also showed higher CEC values (Figure 5). These sites are the major source of all available cations for plant uptake. By comparing data of Table 4 and Figure 6, it can be concluded that treatments having higher organic matter at 60 days of incubation had higher amount of organic matter and thus showing higher CEC in Figure 6 and vice versa. A comparison of manures also shows that the application of KPMC achieved the highest WHC, followed by VAC and BEC. Similarly, the WHC of these samples was also found to be much higher in some samples with organic matter, which may be attributed to higher SOM and higher

CEC than that of the control treatments (Figure 6) because SOM and CEC play a significant role in improving the water holding capacity of soils. In general, soils with higher CEC and SOM content tend to have higher WHC, as they are able to hold onto more water due to their increased ability to cation exchange and absorb water.

3.3. Total Nitrogen (N), available Phosphorus (P), and Potassium (K) (%)

The data on total N, Olsen P, and extractable K are presented in Tables 5, 6 and 7 respectively. These tables illustrate that the individual and combined effects of manure type and incubation period on N, P, and K soil contents are statistically highly significant, indicating that the type of manure significantly influences the release of N, P, and K in the soils during incubation. According to the total N data in Table 5, cups treated with CPM, GMI, VAC, and EPMC had higher total N levels than other manures at the initial incubation stage, which decreased over time. Comparing manures, CPM had the highest total N content (1.40%), followed by VAC (1.01%) and EPMC (0.86%). Cups treated with BEC had the lowest total N content (0.37%), followed by CWS with 0.49% total N (Table 5). Available P exhibited a different trend compared to total N. Among the manure types, cups treated with KOWC had the highest Available P (2.99%), followed by VAC (1.74%), while FYM and BEC had the lowest Available P (0.10% and 0.16%, respectively). The data in Table 6 show that most of the applied organic P is mineralized during the early stages of incubation.

A similar trend was observed for soil K (Table 7), with KOWC and VAC contributing more to K release in soils compared to other organic manures. This suggests a relationship between the release patterns of P and K from the manure. These results could be the outcome of the type of organic manure applied to the soil affecting the mineralization of carbon, nitrogen, phosphorus, and potassium. The data presented in Tables 1, 2, 3, and 4 are consistent with findings in the literature (Hassan et al., 2011; Vimlesh & Giri, 2011; Li & Li, 2014, Joshi et al., 2020; Guo et al., 2020; Gunjal & Gunjal, 2021; Iderawumi & Kamal, 2022). The release of N, P, and K in the initial quarters of incubation was higher and gradually declined in later quarters, with this decline being directly related to the nutrient contents of the applied manures. For example, BEC exhibited the highest soil C content (38.1%) due to its high organic matter content (76%), followed by EPMC and VAC (61%) compared to CWS (4.3%). Manures with higher C content have greater potential to enhance soil C and overall soil health, as discussed by Datta et al. (2018) and supported by Toriyama et al. (2020) through compost and weed incorporation. The higher total N content in soils treated with CPM, GMI, VAC, and EPMC (Table 5) may be attributed to the higher cumulative total N in these manures. Additionally, the C and N contents of manure influence the C:N ratio, which in turn affects N mineralization, as discussed by Vimlesh & Giri (2011) and Ling-ling & Shu-Tian (2014). The variations in soil P and K contents may also be influenced by C and N mineralization.

3.4. Soil water holding capacity

It was observed that the addition of organic manures significantly improved WHC compared to the control (Figure 7). The higher water holding capacity (WHC) of the treated soils may be due to an increase in the soil pores particularly micropores, either by binding soil particles together or by creating favourable conditions for soil organisms (Li et al., 2020; Iderawumi & Kamal, 2022). Organic matter enriched soils act as sponge and can holding up to 90 percent of its weight in water (Zhang et al., 2013).

Table 5. Soil total N (%) at different intervals of incubation of organic manures

Organic manures	Incubation time (days) 3	15	30	45	60	Mean
Control	0.20 t	0.30 rs	0.37 q-s	0.15 tu	0.07 u	0.22 I
FYM	0.54 m-o	0.76 ij	0.97 gh	0.39 q	0.17 t	0.56 F
EPMC	0.78 ij	1.19 e	1.38 d	0.59 l-n	0.34 q-s	0.86 C
CPM	1.39 d	1.83 b	2.11 a	1.04 fg	0.65 kl	1.40 A
GMI	0.71 jk	1.17 e	1.53 c	0.53 no	0.19 t	0.83 D
KOWC	0.66 kl	1.08 f	1.42 d	0.50 o	0.19 t	0.77 E
BEC	0.37 qr	0.52 no	0.61 lm	0.29 s	0.08 u	0.37 H
CWS	0.47 op	0.70 jk	0.79 i	0.36 q-s	0.15 tu	0.49 G
VAC	0.95 h	1.36 d	1.59 c	0.73 i-k	0.41 pq	1.01 B
Mean	0.67 C	0.99 B	1.197 A	0.51 D	0.25 E	

HSD values: Organic manure (A) = 0.0287, Incubation time (B) = 0.0187, A×B = 0.0825, CV = 3.41

F-value / Level of significance: A = **, B = *, A×B = *

Table 6. Available P (%) at different intervals of incubation of organic manures

Organic manures	Incubation time (days)					Mean
	3	15	30	45	60	
Control	0.04 s	0.06 q-s	0.07 q-s	0.03 s	0.02 s	0.05 H
FYM	0.10 p-s	0.14 o-s	0.16 o-s	0.07 q-s	0.05 rs	0.10 G
EPMC	1.07 i	1.49 g	1.81 ef	0.81 j	0.59 k	1.15 C
CPM	0.08 q-s	0.11 o-s	0.13 o-s	0.07 q-s	0.05 rs	0.09 GH
GMI	0.25 no	0.42 lm	0.49 k-m	0.19 o-r	0.14 o-s	0.30 E
KOWC	2.47 c	3.90 b	5.31 a	1.89 e	1.42 gh	2.99 A
BEC	0.15 o-s	0.20 n-q	0.24 n-p	0.12 o-s	0.08 q-s	0.16 F
CWS	0.34 mn	0.50 kl	0.56 kl	0.26 no	0.19 o-r	0.37 D
VAC	1.66 f	2.21 d	2.57 c	1.27 h	0.97 i	1.74 B
Mean	1.26 A	1.00 B	0.69 C	0.52 D	0.39 E	

HSD values: Organic manure (A) = 0.0517, Incubation time (B) = 0.0338, A×B = 0.1485, CV = 5.76
F-value / Level of significance: A = **, B = **, A×B = *

Table 7. Available K (%) at different intervals of incubation of organic manures

Organic manures	Incubation time (days)					Mean
	3	15	30	45	60	
Control*	0.26 xy	0.34 vw	0.23 yz	0.19 z[a]	0.14 [ab]	0.05 H
FYM	1.07 d	1.36 b	0.42 r-u	0.81 f-h	0.61 mn	0.10 G
EPMC	0.30 wx	0.38 t-v	0.44 q-t	0.23 yz	0.17 z[a]	1.15 C
CPM	0.48 p-r	0.66 k-m	0.78 g-i	0.36 u-w	0.27 xy	0.09 GH
GMI	0.72 i-k	0.99 e	1.30 b	0.53 op	0.39 t-v	0.30 E
KOWC	0.46 q-s	0.57 no	0.70 j-l	0.35 vw	0.27 xy	2.99 A
BEC	0.55 n-p	0.74 h-j	0.87 f	0.40 s-v	0.30 wx	0.16 F
CWS	0.83 fg	1.04 de	1.23 c	0.64 lm	0.49 pq	0.37 D
VAC	0.10 [b]	0.14 [ab]	0.20 yz[a]	0.08 [b]	1.61 a	1.74 B
Mean	0.69 C	1.00 B	1.26 A	0.52 D	0.39 E	

HSD values: Organic manure (A) = 0.0230, Incubation time (B) = 0.0150, A×B = 0.0662, CV = 0.5561
F-value / Level of significance: A = **, B = **, A×B = ** Note: Control = soil without manures, * significant, ** highly significant, FYM (Farmyard manure), EPMC (Enriched Poultry manure compost), CPM (Composted press mud), GMI (Green manure i.e. berseem incorporated), KOWC (Kitchen organic waste compost), BEC (Biochar enriched compost), CWS (Composted wheat straw), VAC (Value added compost).

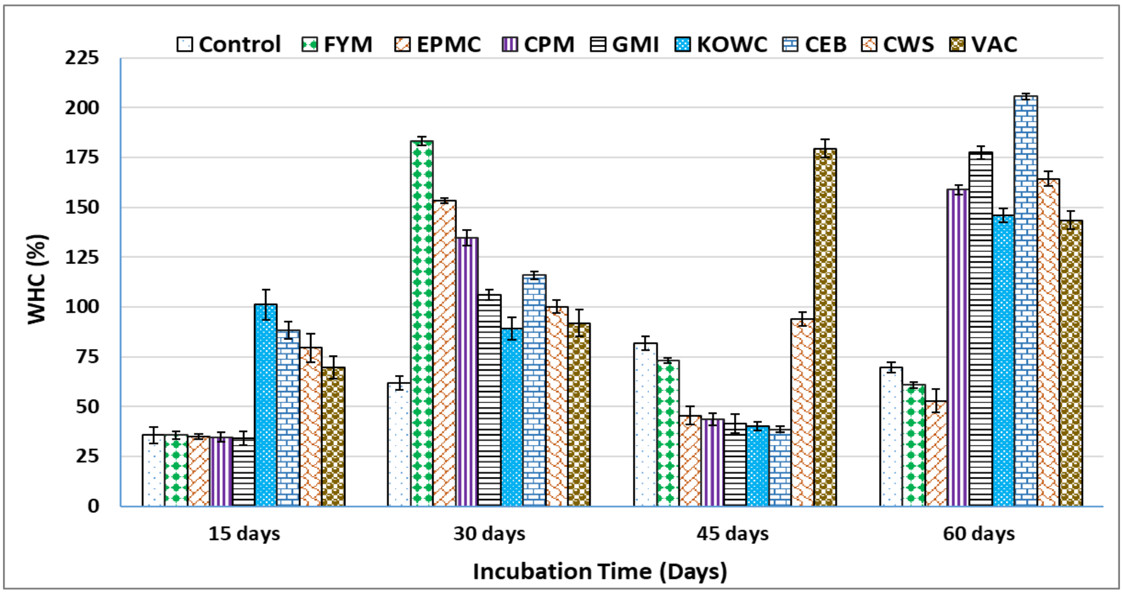

Figure 7. Variations in soil WHC due to addition organic manures under controlled conditions [28±3°C, mean effect].
Whereas: FYM (Farmyard manure), EPMC (Enriched Poultry manure compost), CPM (Composted press mud), GMI (Green manure i.e. berseem incorporated), KOWC (Kitchen organic waste compost), BEC (Biochar enriched compost), CWS (Composted wheat straw), VAC (Value added compost)
* without organic manure

3.5. Relationship between C: N Ratio and Manure Mineralization

The release of nutrients from organic manures is influenced by the C: N ratio. The C:N ratio determines whether a nutrient will be mineralized or immobilized after the addition of organic manure. Figure 8 illustrates the relationship between the C:N ratio and the rate of N mineralization in the manures. Figure 8 shows that the rate of N mineralization (NMR) varies with the C:N ratio of the applied organic manures. Most of the N mineralization in farmyard manure (FYM) and enriched press mud cake (EPMC) occurred when the C:N ratio was ≥10. In contrast, most of the N mineralization in cattle pen manure (CPM), goat manure (GMI), kitchen organic waste compost (KOWC), banana waste compost (BEC), and vegetable waste compost (VAC) occurred at C:N ratios ≤5. Comparing the NMR values among different organic manure types, it was observed that the highest NMR was in CPM, while the lowest NMR was in BEC. The R2 values indicate that these relationships are not consistently strong across all scenarios.

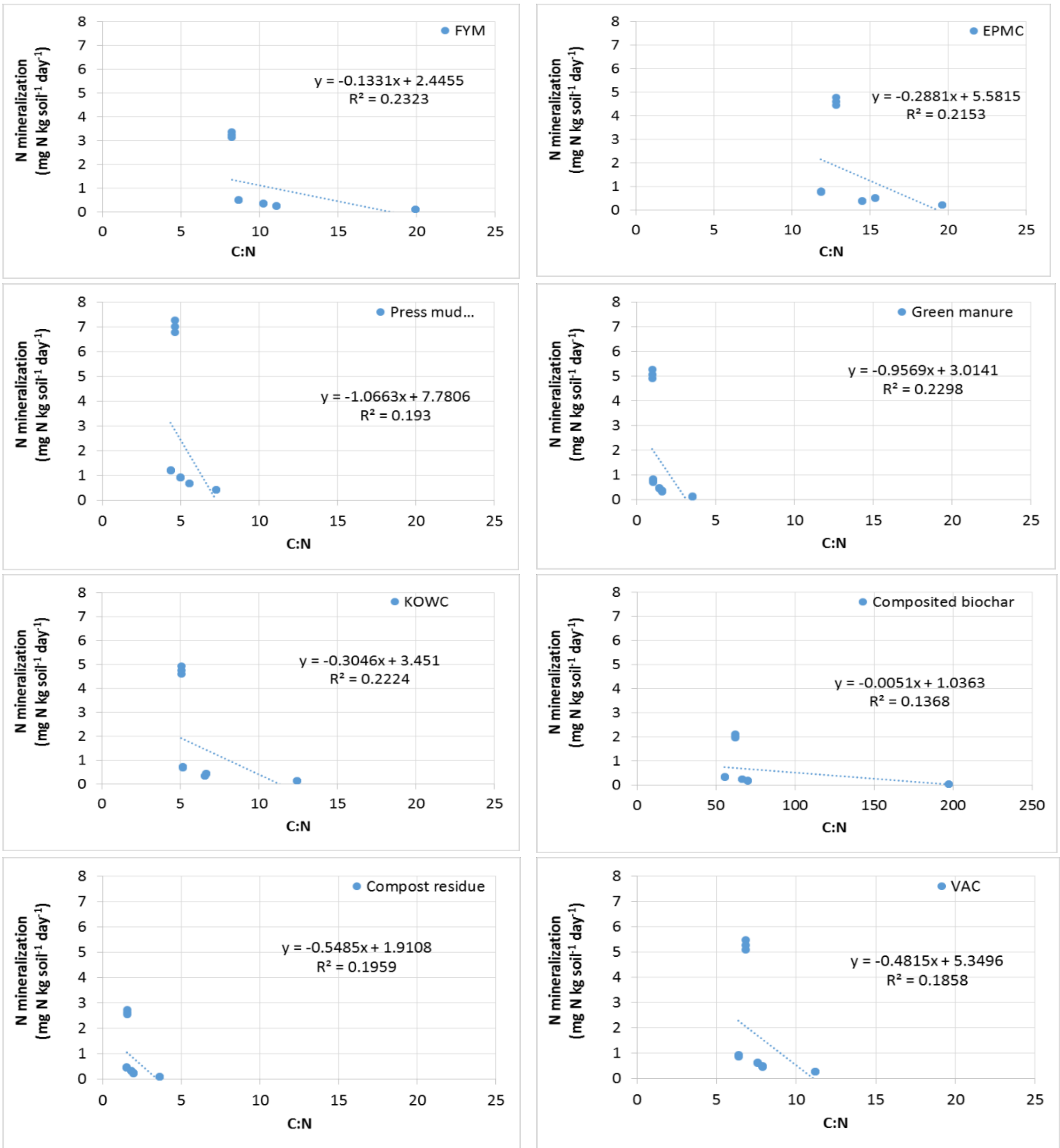

Figure 8. Relationship between N mineralization rate (NMR) and C:N ratio of manures

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Therefore, these relationships may not be reliable for predicting NMR when using composted organic manures, as most of these manures have a C:N ratio of less than 25 (as shown in Table 1), suggesting that they will provide N directly to plants upon application. However, the trend lines depicted in Figure 8 can assist researchers or managers in determining the appropriate N supply to plants when their demand is at its peak. Similar to C: N and NMR (Figure 8), the rate of P mineralization (PMR) varied among different types of manure (Figure 8). Figure 9 also illustrates that the relationship between PMR and C:P is weak, as indicated by the low R2 values in all relationships. However, like C: N, C: P can still be used as a tool to manage P supply according to crop demand.

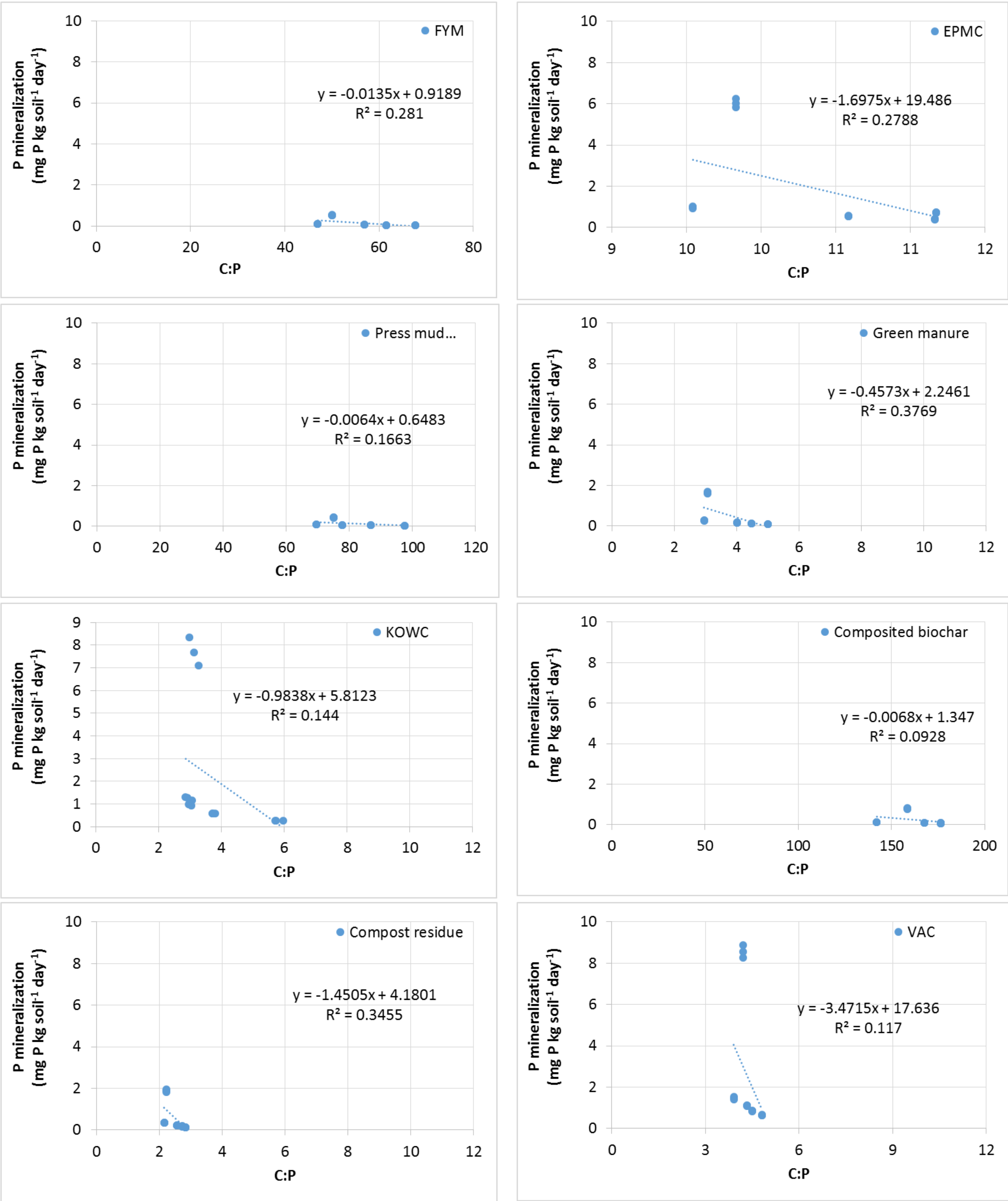

Figure 9. Relationship between P mineralization and C:P ratio of manures

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Manures such as FYM, CPM, and BEC released P when C:P was ≥ 40, suggesting that these manures can provide a quick supply of P to plants. On the other hand, manures like VAC, CWS, KOWC, GMI, and EPMC can be utilized for integrated P management in plants. Figure 9 also demonstrates that EPMC, VAC, and KOWC are suitable sources for supplying P at a higher rate to meet the P demand of plants.

Figure 10 showed the relationship between P mineralization as result of N mineralization.

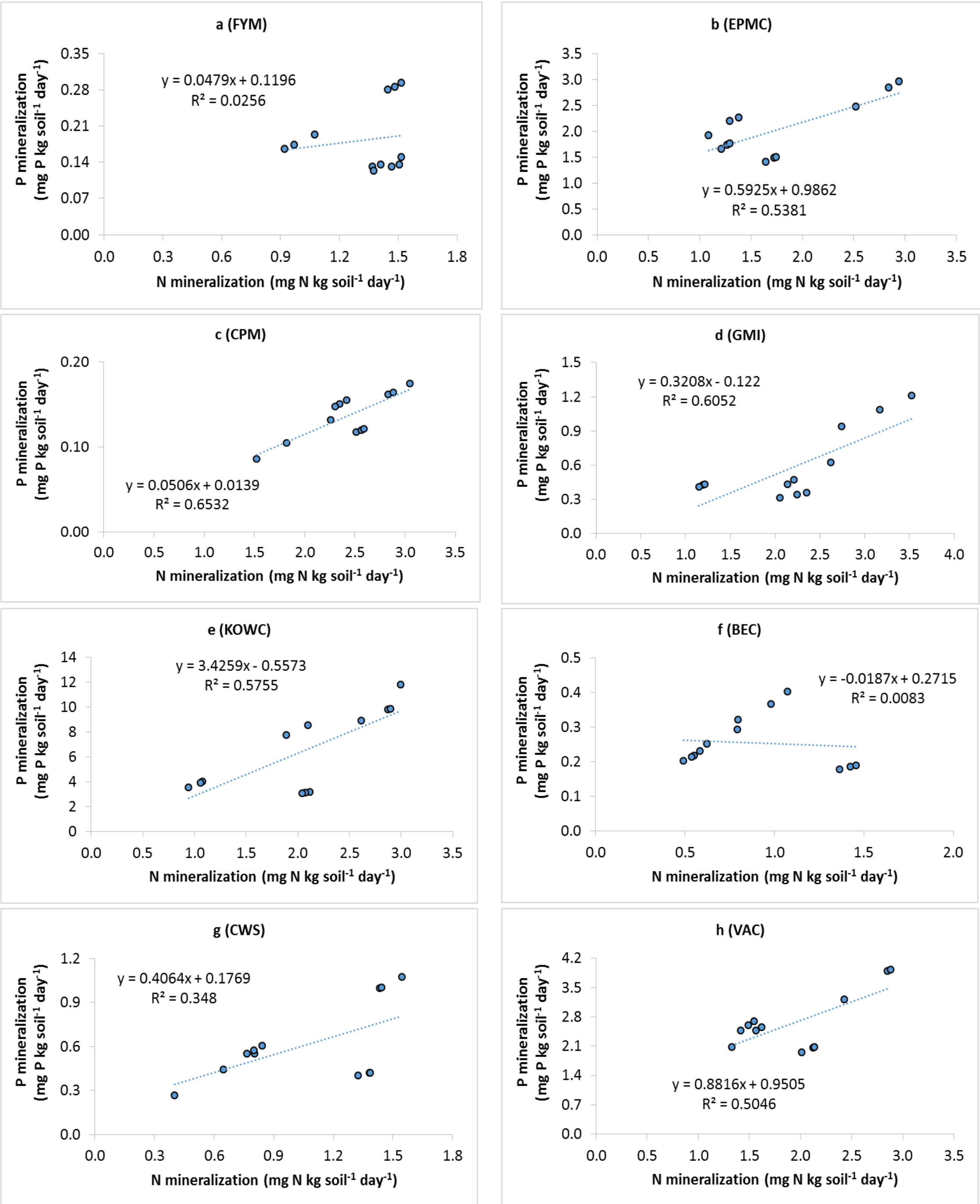

Figure 10. Relationship between N mineralization rate (NMR) and P mineralization rate (PMR) of organic manures during a 60-day incubation period

To explore the reasons for variations in NMR and PMR, the relationship between the two was examined. The degree of association between NMR and PMR varied depending on the type of manure (Figure 10). The association was very weak for FYM (Figure 10a), BEC (Figure 10f), and CWS (Figure 10g), but moderately strong for EPMC (Figure 10b), CPM (Figure 10c), GMI (Figure 10d), KOWC (Figure 10e), and VAC (Figure 10h).

These findings suggest that N and P mineralization rates (Figures 8, 9 & 10) are influenced by the type and nature of organic manure (Table 1).

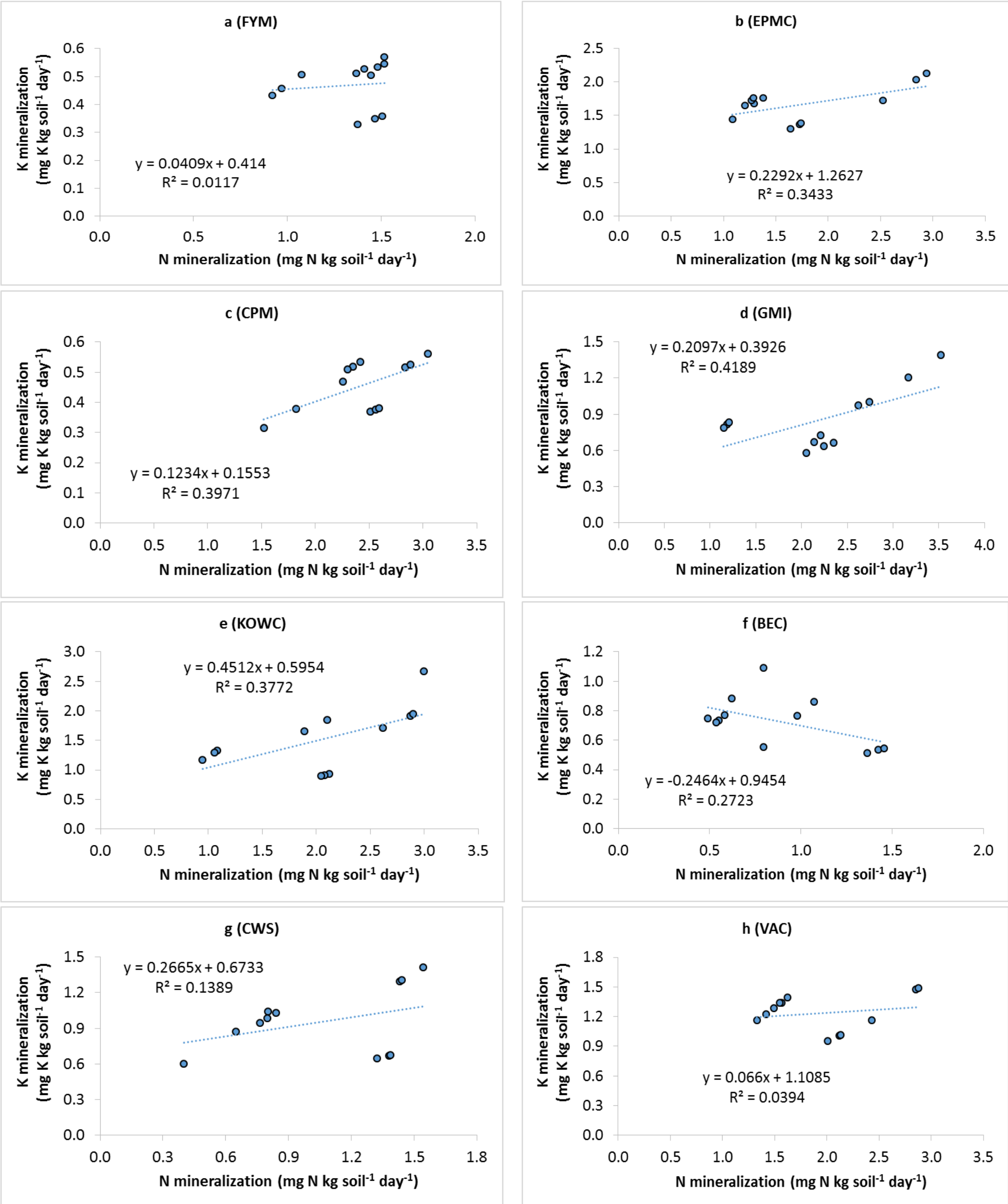

Figure 11. Relationship between N mineralization rate (NMR) and K mineralization rate (KMR) of organic manures during a 60-day incubation period

Similarly, the correlation between K mineralization rate (KMR) and NMR was found to be weak (Figure 11). In contrast to the relationships between NMR, PMR, and KMR, a peculiar trend was observed for PMR and KMR (Figure 12), showing a strong correlation with NMR with R2 ≥ 60, except for FYM and BEC. Such findings were also reported by Vimlesh & Giri (2011), Li & Li (2014) and Toriyama et al. (2020).
Pearson's correlation analysis was used to determine the associations between different variables (Table 8). The table indicated that soil C, SOM, total N, available P, and available K were significantly positively correlated with manure type but significantly negatively correlated with incubation time. Additionally, both C: N and C: P ratios were positively correlated with manure type and incubation time, while the correlation between C:P and both variables was non-significant. These correlations suggest that the type of manure may have a greater impact than incubation time on variations in C, N, P, and K mineralization.

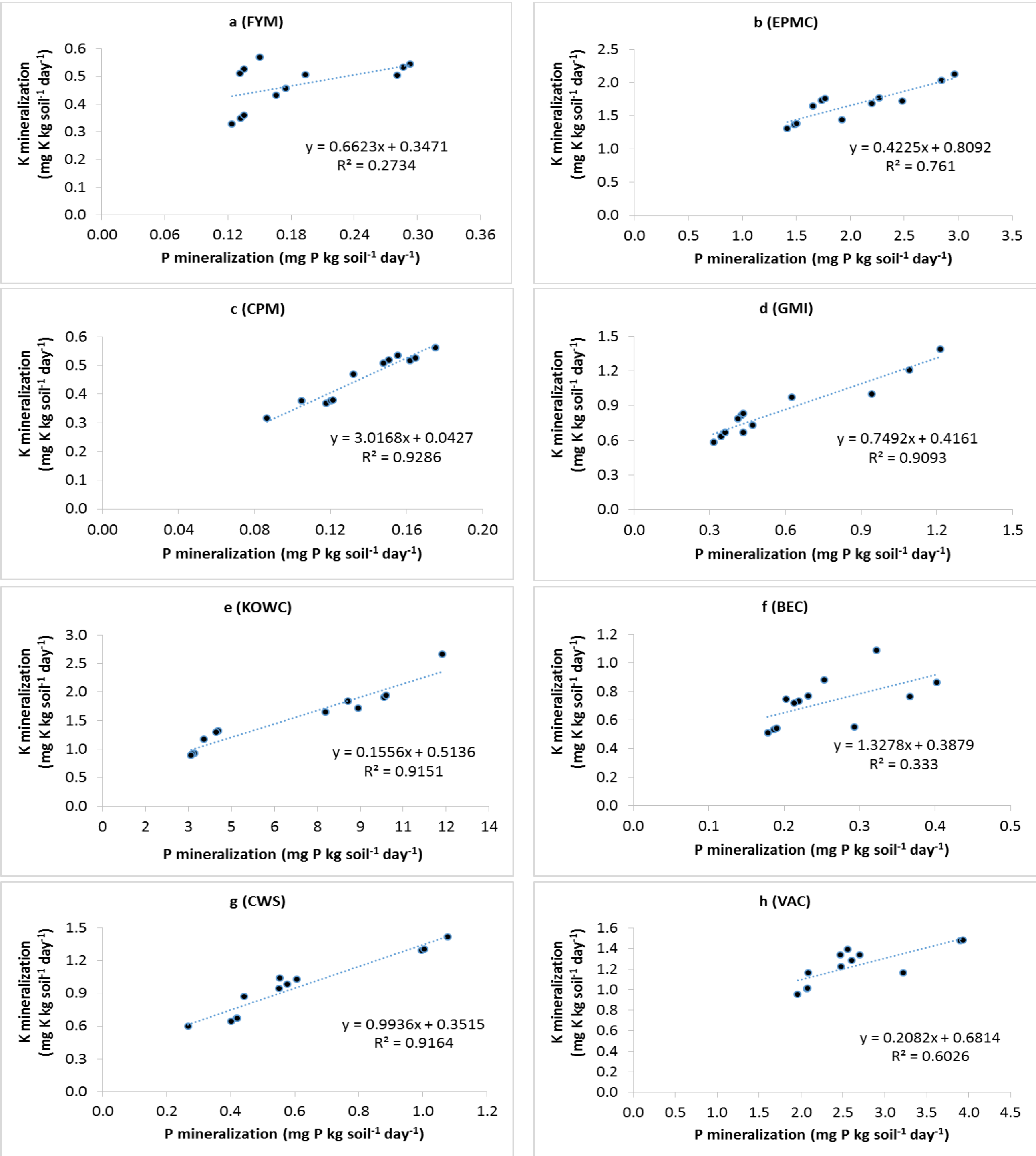

Figure 12. Relationship between P mineralization rate (PMR) and K mineralization rate (KMR) of organic manures during a 60-day incubation period

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Table 8. Pearson's correlation of SOM, Soil C, total N, Olsen P, available K, C:N and C:P with manure type and incubation time

	Organic Manure	Inc. time	Soil C	SOM	Total N	Olsen P	Available K	C:N
Soil C	0.2115	-0.2667						
	0.0138	*0.0018*						
SOM	0.2115	-0.2667	1.0000					
	0.0138	*0.0018*	*0.0000*					
Total N	0.1162	-0.6759	0.1305	0.1305				
	0.1794	*0.0000*	*0.1313*	*0.1313*				
Olsen P	0.3325	-0.2857	0.0323	0.0323	0.3796			
	0.0001	*0.0008*	*0.7097*	*0.7097*	*0.0000*			
Available K	0.3473	-0.5402	0.3050	0.3050	0.5642	0.7209		
	0.0000	*0.0000*	*0.0003*	*0.0003*	*0.0000*	*0.0000*		
C:N	0.2015	0.1819	0.5829	0.5829	-0.2722	-0.1488	-0.0924	
	0.0191	*0.0347*	*0.0000*	*0.0000*	*0.0014*	*0.0850*	*0.2865*	
C:P	0.0479	0.0603	0.7315	0.7315	-0.0904	-0.3668	-0.2904	0.7403
	0.5812	*0.4875*	*0.0000*	*0.0000*	*0.2970*	*0.0000*	*0.0006*	*0.0000*

Pearson's correlation also showed that C:N and C:P exhibit a negative correlation with total N, available P, and available K, which may be attributed to the composted form of applied manures.

Table 8 also reveals that total N and available P are non-significantly correlated with soil C and SOM, indicating that N and P mineralization may be influenced by other factors such as initial N and P contents of manures, accelerated microbial activity, or increased moisture retention in the soil. These correlations emphasize the impact of nutrient release patterns on the nutrient status of manure, microbial community, and other physical properties of the soils. Similar findings were also reported by Joshi et al. (2020), Guo et al. (2020) and Cheng et al. (2023).

4. Conclusion

The present study provides clear evidence that the eight manure types differ markedly in their effects on soil organic matter, soil carbon dynamics, and nutrient mineralization rates (NMR, PMR, and KMR). These differences are primarily driven by the intrinsic chemical composition of each manure source, highlighting that organic amendments cannot be regarded as nutritionally uniform inputs.

The observed variability in nutrient release patterns further indicates that no single manure type can be universally recommended for integrated nutrient management of N, P, or K. Instead, nutrient specific calibration and characterization of manure sources should be prioritized in future research. Based on the observed nutrient mineralization behavior, EPMC emerged as the most suitable organic amendment for integration with chemical N fertilizers, providing a more synchronized N release pattern. KOWC showed superior potential as an organic source for integrated P management, while BEC demonstrated higher efficiency as a K-rich organic amendment.

Additionally, VAC displayed balanced and consistent nutrient release characteristics, making it a strong candidate for use as a general-purpose organic nutrient source. These findings highlight the significance of manure-specific nutrient profiling to optimize integrated nutrient management strategies, improve fertilizer use efficiency, and promote sustainable soil fertility enhancement.

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Authors Contribution

Rashid conducted this study as part of his PhD degree under the supervision of Wazir Ahmed, who planned the research, assisted in writing up the study, and conducted statistical analysis. Tanveer Ul Haq and Shafqat Saeed provided technical guidance, while Ashfaq Ahmad Rahi assisted with composting and VAC preparation. Abdul Ghaffar offered technical support during the incubation study.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they are no conflict of interest associated with this study.

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