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SOIL CHEMICAL RESPONSES TO MD2 PINEAPPLE-WASTE COMPOSTS PRODUCED USING DIFFERENT COMPOSTING TECHNIQUES

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ABSTRACT. *Pineapple residues can be converted into soil amendments, but composting method may determine whether the resulting product mainly ameliorates acidity or increases nutrient availability. This study compared ground magnesium limestone (GML)-enhanced compost, indigenous microorganisms (IMO) compost and vermicompost produced from MD2 pineapple waste for their effects on a Typic Paleudult. A four-treatment by three-period factorial experiment was arranged in a completely randomised design with destructive sampling after 20, 40 and 60 days and three replicates per combination. Each amended unit contained 200 g soil and 10 g compost. Treatment significantly affected soil pH, electrical conductivity (EC), available potassium (K) and available phosphorus (P). Incubation period and the treatment × period interaction affected EC, K and P but not pH. GML-enhanced compost maintained the highest pH (6.40–6.57), whereas the control remained strongly acidic. Vermicompost produced the highest Day-60 EC and available K and P, reaching 22.33 and 53.67 mg kg^{-1}, respectively. The results indicate that GML-enhanced compost functioned mainly as an acidity-correcting amendment, whereas vermicompost produced the strongest nutrient-availability response. Greenhouse and field validation is required before practical recommendations are made.*

INTRODUCTION

Pineapple (*Ananas comosus*) cultivation and processing generate leaves, stems, crowns, peels, cores and rejected fruit. These residues contain fibre, soluble carbon and plant nutrients, but unmanaged accumulation can produce odour, leachate and greenhouse-gas emissions.

Resource-recovery approaches therefore increasingly emphasise conversion into compost, vermicompost, animal feed, fibres, enzymes and bioenergy rather than disposal (Aili Hamzah et al., 2021; Sarangi et al., 2023). Sossa et al. (2024) further demonstrated that the quality of pineapple-residue compost is strongly influenced by feedstock composition and composting conditions.

Composting stabilises moist organic residues and produces a material that can be returned to soil, but products derived from the same crop residue need not have the same agronomic function. Aeration, moisture, acidity, biological activity, mineral additives and degree of stabilisation can alter pH, soluble-ion concentration and nutrient composition (Nguyen et al., 2021; López et al., 2021; Sossa et al., 2024). This variability is particularly relevant when composts are intended for strongly weathered acidic soils.

The three composting approaches evaluated here were selected because they act through contrasting mechanisms. Ground magnesium limestone (GML) supplies calcium- and magnesium-bearing carbonates that neutralise acidity and are expected to increase soil pH. Indigenous microorganisms (IMO) are used to stimulate microbial decomposition and nutrient transformation. Vermicomposting combines microbial activity with the feeding, fragmentation and casting activity of *Eisenia fetida* and can produce a more stabilised material with a narrower carbon-to-nitrogen ratio and higher nutrient concentration. Accordingly, the method used to produce the amendment may influence soil pH, electrical conductivity (EC), available potassium (K) and available phosphorus (P) through different chemical and biological pathways.

These contrasts are important for *Typic Paleudults*, which are strongly weathered and acidic and may have low base status, exchangeable aluminium and strong phosphate retention. A carbonate-bearing amendment may correct acidity without supplying the largest quantity of K or P, whereas a nutrient-rich biological amendment may increase extractable nutrients without producing the strongest liming effect. Regasa et al. (2025) similarly showed that lime and vermicompost can improve different aspects of soil chemical fertility in acidic soils.

Direct comparisons of GML-enhanced compost, IMO compost and vermicompost produced from the same MD2 pineapple feedstock and applied at an identical mass rate to the same acidic soil remain limited. This study therefore compared their effects on soil pH and EC and evaluated treatment, incubation-period and treatment × period effects on available K and P. It was hypothesised that GML-enhanced compost would produce the greatest and most stable pH increase, IMO compost would produce an intermediate chemical response, and vermicompost would produce the greatest late-incubation EC and available K and P because of its more advanced biological processing and nutrient composition.

MATERIALS AND METHODS

Compost Production and Characterisation

The three pineapple-waste amendments were produced in a companion 98-day (14-week) composting experiment at the MD2 Pineapple Research Plot, Faculty of Plantation and Agrotechnology, Universiti Teknologi MARA Pahang Branch, Jengka Campus. Fresh MD2 pineapple residues, including peels, overripe fruit and crowns, were combined with older partially dried crowns, leaves and fibrous residues. The materials were manually chopped to approximately 3–5 cm, mixed thoroughly, and approximately 1 kg of mixed feedstock was placed in each 50-L polystyrene box. For GML-enhanced compost, GML was applied at 50 g kg^{-1} feedstock (5% w/w). The IMO compost received cultured IMO solution at 100 mL kg^{-1} feedstock. For vermicomposting, the material was conditioned to avoid excessive acidity and heat before approximately 50 *E. fetida* were introduced per kilogram of feedstock. Boxes were

kept under sheltered ambient tropical conditions. GML and IMO treatments were turned once weekly, whereas disturbance of the vermicompost was minimised. Moisture was monitored and adjusted with water when necessary; temperature, moisture and pH were monitored during composting. Stabilisation was assessed using temperature approaching ambient conditions, dark-brown colour, crumbly texture, reduced odour and the final carbon-to-nitrogen (C:N) ratio. The final characteristics of the three composts used in the incubation are summarised in Table 1.

Table 1. Selected final physicochemical properties of the pineapple-waste composts used in the incubation.

Property	GML-enhanced compost	IMO compost	Vermicompost
pH	7.30	6.70	6.90
Moisture (%)	57.33	57.00	72.00
Final temperature (°C)	30.67	29.67	27.67
Total N (%)	1.35	1.55	1.75
Total P (%)	0.29	0.34	0.39
Total K (%)	1.55	1.75	1.85
Total C (%)	31.31	29.57	27.84
C:N ratio	23.06	19.02	15.88

Note. Values are means of three compost-production units. N = nitrogen; P = phosphorus; K = potassium; C = carbon.

Soil Preparation and Initial Properties

A mineral soil classified as a *Typic Paleudult* was collected from an uncultivated area at Universiti Teknologi MARA Pahang Branch, Jengka Campus, from the 0–15 cm layer. The soil was air-dried, passed through a 2-mm sieve and homogenised. Before amendment application, the bulk soil was characterised for its initial physicochemical properties (Table 2).

Table 2. Initial physicochemical properties of the *Typic Paleudult* used in the incubation study.

Property	Unit	Initial value
pH (water)	–	4.61
pH (KCl)	–	3.95
Electrical conductivity	µS cm^{-1}	35.1
Bulk density	g cm^{-3}	1.25
C:N ratio	–	27:1
Total organic carbon	%	2.16
Total nitrogen	%	0.08
Total phosphorus	mg kg^{-1}	22.25
Total potassium	mg kg^{-1}	101.27
Cation exchange capacity	cmol kg^{-1}	4.67
Exchangeable K^{+}	cmol kg^{-1}	0.06
Exchangeable Ca^{2+}	cmol kg^{-1}	0.02
Exchangeable Mg^{2+}	cmol kg^{-1}	0.22
Exchangeable Na^{+}	cmol kg^{-1}	0.03
Exchangeable Fe^{2+}	cmol kg^{-1}	1.09
Exchangeable acidity	cmol kg^{-1}	1.15
Exchangeable H^{+}	cmol kg^{-1}	0.13
Exchangeable Al^{3+}	cmol kg^{-1}	1.02

Note. Particle-size distribution was 71.9% sand, 13.5% silt and 14.6% clay; textural class = sandy loam. Initial phosphorus and potassium values represent total soil contents, whereas phosphorus and potassium measured during incubation were Mehlich-3 available forms.

Experimental Design

The soil incubation followed a 4 × 3 factorial completely randomised design. Factor 1 was compost treatment with four levels: GML-enhanced compost (T1), IMO compost (T2), vermicompost (T3) and unamended soil (T4). Factor 2 was incubation period with three levels: 20, 40 and 60 days. Each treatment × period combination had three independent soil-incubation

replicates. Because sampling was destructive, a separate container was prepared for each combination, giving 36 incubation units. Each unit contained 200 g dry soil; amended treatments received 10 g compost, equivalent to 5% (w/w) of soil dry mass. The three composts were applied at the same mass rate, so differences in their nutrient composition formed part of the treatment comparison.

Each composting method was initially produced in three 50-L boxes. At the end of the composting period, the three replicates within each method were homogenised to obtain one composite amendment for each compost type. These composite GML-enhanced compost, IMO compost and vermicompost materials were then used in the soil-incubation experiment.

Table 3. Compost treatments and amendment rates used in the 4 × 3 factorial incubation.

Code	Treatment	Soil per unit	Amendment per unit
T1	Ground magnesium limestone-enhanced pineapple-waste compost	200 g	10 g
T2	Indigenous microorganism pineapple-waste compost	200 g	10 g
T3	Pineapple-waste vermicompost	200 g	10 g
T4	Unamended soil control	200 g	None

Note. Factor 1 = treatment (four levels, T1–T4); Factor 2 = incubation period (20, 40 and 60 days). Three independent incubation replicates were used for each treatment × period combination, giving 36 units.

Incubation and Sampling

Soil-compost mixtures were placed in perforated plastic containers to permit gas exchange while limiting rapid moisture loss. Distilled water was added to 60% of field capacity. Containers were weighed regularly and re-watered when necessary. Three replicate containers per treatment were destructively sampled after 20, 40 and 60 days; soil from each container was mixed, air-dried and stored before analysis. Initial properties of the unamended bulk soil are presented in Table 2. Treatment-specific Day-0 measurements were not collected after compost incorporation, so changes among treatments were evaluated from Day 20 onwards. The unamended treatment at each sampling date served as the control.

Soil Chemical Analyses

Soil pH was measured in a 1:2.5 soil-to-distilled-water suspension using a calibrated digital pH meter after mixing and equilibration (Soil Survey Staff, 2022). Electrical conductivity was measured in a standardised soil-water extract using a calibrated conductivity meter and expressed as µS cm^{-1} (Soil Survey Staff, 2022). Available K and P were extracted using Mehlich-3 solution (Mehlich, 1984), and concentrations in filtered extracts were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) using established multielement procedures (U.S. Environmental Protection Agency, 2018). The measured soil variables were pH, EC, available K and available P; mineral nitrogen was not determined.

Statistical Analysis

Data were analysed using two-way analysis of variance (ANOVA), with compost treatment as a four-level factor and incubation period as a three-level factor. The model tested treatment, incubation-period and treatment × period effects for each response variable. Where treatment means differed within an incubation period, means were separated using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$. Results are presented as means ± standard error.

RESULTS AND DISCUSSION

Table 4. Summary of two-way analysis of variance for selected soil chemical properties.

Parameter	Source of variation	df	F-value	p-value	Significance
Soil pH	Treatment	3	87.55	<0.0001	*
	Incubation period	2	0.01	0.9898	ns
	Treatment × period	6	0.22	0.9664	ns
Electrical conductivity	Treatment	3	11.41	<0.0001	*
	Incubation period	2	7.38	0.0032	*
	Treatment × period	6	4.59	0.0031	*
Available potassium	Treatment	3	137.53	<0.0001	*
	Incubation period	2	14.56	<0.0001	*
	Treatment × period	6	7.91	<0.0001	*
Available phosphorus	Treatment	3	50.33	<0.0001	*
	Incubation period	2	12.14	0.0002	*
	Treatment × period	6	11.25	<0.0001	*

*Note. * Significant at $p < 0.05$; ns = not significant.*

Effect of Compost Treatments on Soil pH

Compost treatment significantly affected soil pH ($F = 87.55$, $p < 0.0001$), whereas incubation period ($p = 0.9898$) and the treatment × period interaction ($p = 0.9664$) were not significant (Table 4). GML-enhanced compost produced the highest pH at every sampling date, ranging from 6.40 to 6.57, while the unamended soil remained strongly acidic at 4.30–4.37 (Figure 1). IMO compost and vermicompost produced intermediate pH values. Thus, the treatment ranking was established by Day 20 and remained broadly stable through Day 60.

The stronger pH response of the GML-enhanced compost is consistent with both its production method and its final properties. The compost contained a direct carbonate source and had a final pH of 7.30, whereas the IMO compost and vermicompost had final pH values of 6.70 and 6.90, respectively (Table 1). Carbonate dissolution consumes acidity and supplies calcium and magnesium, allowing the GML treatment to neutralise the initially acidic soil (pH 4.61; Table 2) more effectively than the biologically processed amendments. Similar increases in pH following lime or GML application to acidic soils have been reported by Panhwar et al. (2020), Mosharrof et al. (2021) and Regasa et al. (2025).

The biologically processed composts also increased pH above the control, but their effects were smaller. Organic amendments can supply base cations, complex aluminium and consume protons during decomposition, while organic functional groups may also release protons; the net effect depends on feedstock and maturity (López et al., 2021). Because treatment-specific Day-0 measurements were not available, the timing of the initial pH response cannot be resolved more precisely than the first sampling at Day 20. The similar treatment ranking from Day 20 to Day 60 indicates that pH had stabilised relatively early in the incubation.

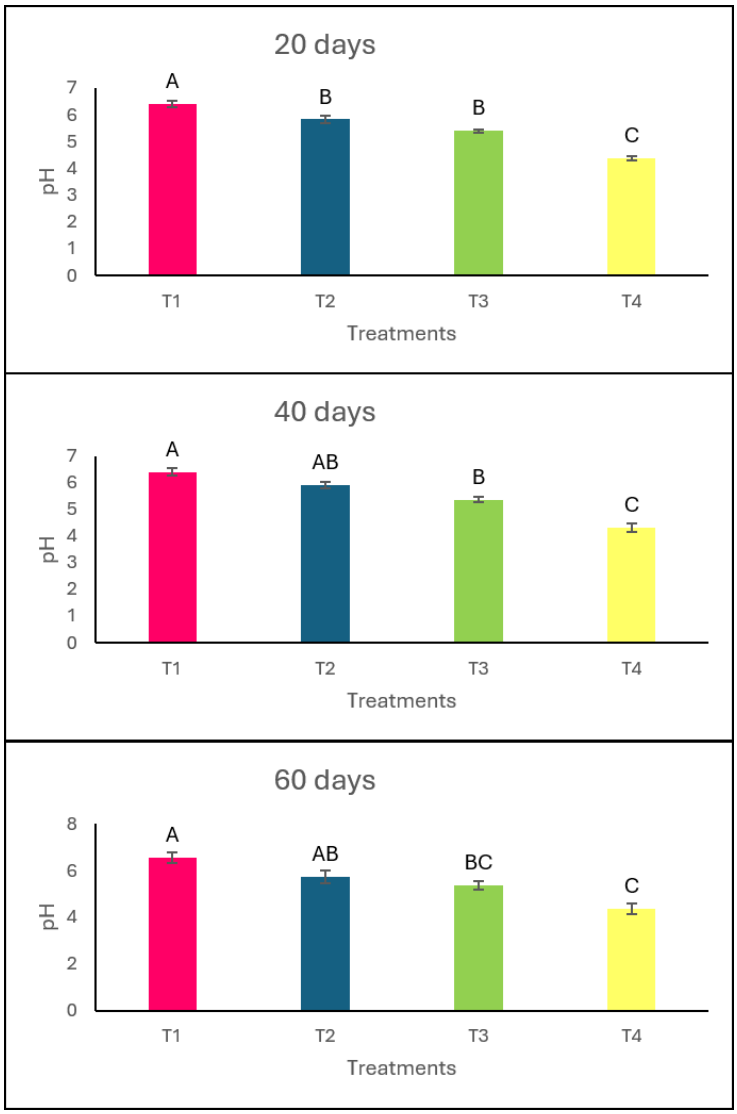

Figure 1. Effect of compost treatments on soil pH at 20, 40 and 60 days. Bars represent means ± standard error; means sharing the same letter within a sampling date are not significantly different according to Tukey's honestly significant difference test at $p \leq 0.05$.

Effect of Compost Treatments on Soil Electrical Conductivity

Compost treatment ($F = 11.41$, $p < 0.0001$), incubation period ($F = 7.38$, $p = 0.0032$) and the treatment × period interaction ($F = 4.59$, $p = 0.0031$) significantly affected EC (Table 4). On Day 20, vermicompost recorded the highest EC (124.0 µS cm^{-1}) and the control the lowest (92.0 µS cm^{-1}). Treatment means converged on Day 40. By Day 60, vermicompost increased to 186.7 µS cm^{-1} and was significantly higher than the other treatments, which remained at approximately 100–125 µS cm^{-1} (Figure 2). The significant interaction therefore reflects the late separation of vermicompost rather than a uniform increase across treatments.

Electrical conductivity reflects the combined concentration of dissolved ions rather than a single nutrient. In the absence of crop uptake and under controlled moisture, the Day-60 increase under vermicompost is consistent with accumulation of soluble products during continued organic-matter transformation. This interpretation is supported by the K and P results, which were also highest in vermicompost at Day 60. The vermicompost had the narrowest C:N ratio (15.88) and the highest total N, P and K concentrations among the three amendments (Table 1), characteristics consistent with a more nutrient-rich and biologically processed material. Earthworm activity can enhance nutrient turnover in organic amendments (Ratsiatosika et al., 2024).

All EC values remained below 0.20 dS m^{-1}, indicating a low soluble-salt concentration under the incubation conditions. The increase in EC under vermicompost on Day 60 coincided with higher available K and P, consistent with a greater accumulation of soluble ions. In contrast, GML-enhanced compost produced a much larger pH response without a comparable increase in EC, showing that acidity neutralisation and soluble-ion accumulation were governed by different amendment properties.

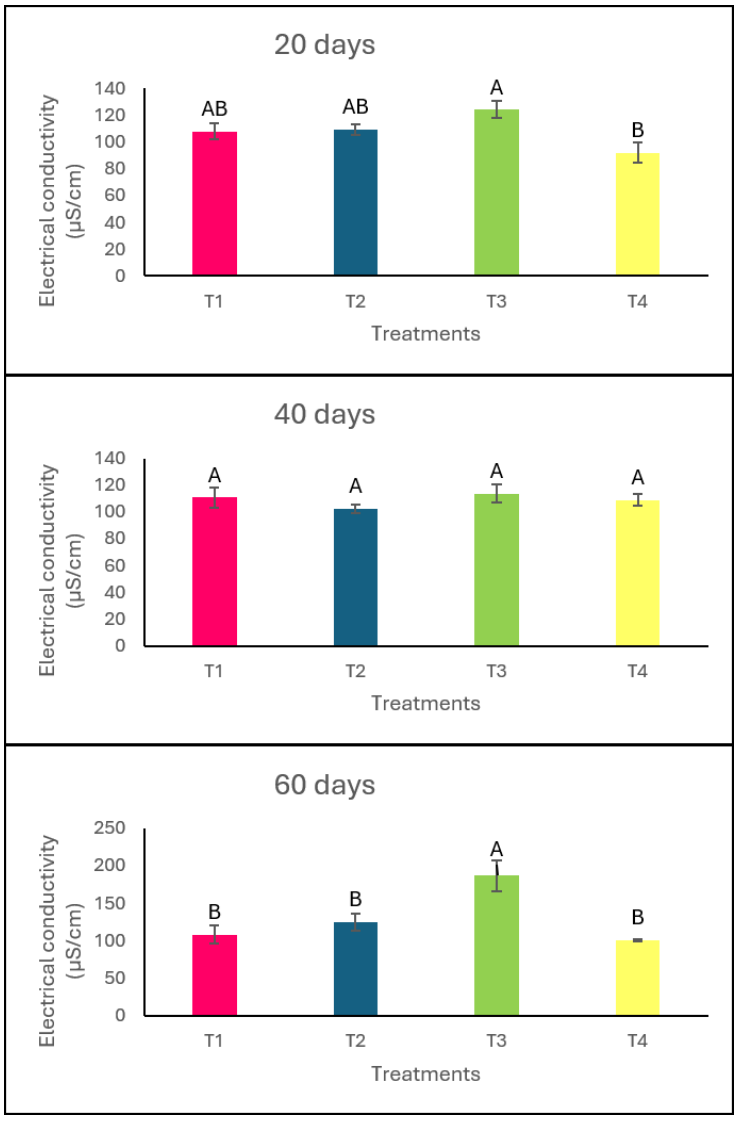

Figure 2. Effect of compost treatments on soil electrical conductivity at 20, 40 and 60 days. Bars represent means ± standard error; means sharing the same letter within a sampling date are not significantly different according to Tukey's honestly significant difference test at $p \leq 0.05$.

Effect of Compost Treatments on Soil Available Potassium

Available K was significantly affected by compost treatment ($F = 137.53$, $p < 0.0001$), incubation period ($F = 14.56$, $p < 0.0001$) and their interaction ($F = 7.91$, $p < 0.0001$) (Table 4). IMO compost and vermicompost produced higher available K than the GML-enhanced compost and control at Days 20 and 40, with no clear separation between the two biological treatments. By Day 60, vermicompost had separated from the other treatments and reached 22.33 mg kg^{-1}; IMO compost remained intermediate, whereas the GML-enhanced compost and control remained comparatively low (Figure 3).

Potassium in plant residues occurs largely as soluble K^+ in cell sap rather than as a structural component, so it can become extractable as tissues break down. The finished composts contained 1.55%

K in the GML-enhanced compost, 1.75% in the IMO compost and 1.85% in the vermicompost (Table 1). Because the amendments were applied at the same mass rate rather than at an equal K dose, the soil response reflects both the nutrient composition of each finished product and transformations during incubation. The greater K concentration and narrower C:N ratio of vermicompost are consistent with its stronger Day-60 response. Vermicompost-induced increases in exchangeable or available K have likewise been linked to amendment composition and nutrient turnover (Das et al., 2022). By contrast, GML primarily supplies calcium and magnesium rather than K; therefore, a strong liming effect does not necessarily produce the greatest K availability.

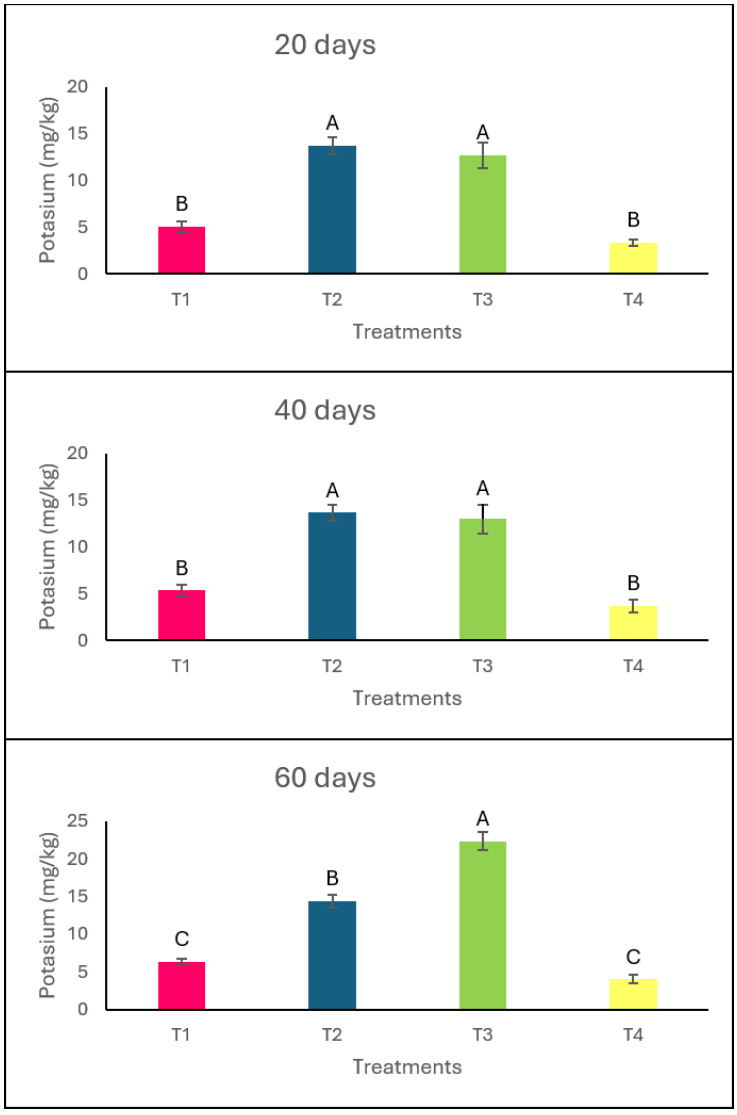

Figure 3. Effect of compost treatments on soil available potassium at 20, 40 and 60 days. Bars represent means ± standard error; means sharing the same letter within a sampling date are not significantly different according to Tukey's honestly significant difference test at $p \leq 0.05$.

Effect of Compost Treatments on Soil Available Phosphorus

Available P was significantly affected by compost treatment ($F = 50.33$, $p < 0.0001$), incubation period ($F = 12.14$, $p = 0.0002$) and the treatment × period interaction ($F = 11.25$, $p < 0.0001$) (Table 4). Vermicompost produced the highest available P at every sampling date. It reached 19.67 mg kg^{-1} on Day 20 and increased to 53.67 mg kg^{-1} on Day 60, approximately three times the concentration under IMO compost and more than nine times that in the control (Figure 4). The stronger late increase under vermicompost accounts for the significant interaction.

Phosphorus behaviour in a *Typic Paleudult* depends on both P input and retention by iron and aluminium oxides. Organic amendments may increase availability by supplying P, complexing aluminium and iron, competing for adsorption sites and changing pH, while mineralisation and temporary immobilisation occur concurrently (Mabagala and Mng'ong'o, 2022; Omenda et al., 2021). The finished composts contained 0.29% P in the GML-enhanced compost, 0.34% in the IMO compost and 0.39% in the vermicompost, while their C:N ratios were 23.06, 19.02 and 15.88, respectively (Table 1). Thus, vermicompost combined the largest P concentration with the narrowest C:N ratio, providing a plausible basis for its greater late-incubation P availability.

Low-molecular-weight organic acids released during decomposition may alter phosphate retention by occupying reactive oxide surfaces or complexing iron and aluminium. Liang et al. (2024) showed that these compounds can influence phosphate retention by iron (hydr)oxides. In the present study, GML-enhanced compost raised soil pH more strongly than the biological composts but did not produce the highest available P, indicating that pH correction alone did not determine P availability. The greater P concentration and narrower C:N ratio of vermicompost likely contributed to its stronger P response. Regasa et al. (2025) also reported contrasting effects of lime and vermicompost on phosphorus availability in acidic soil.

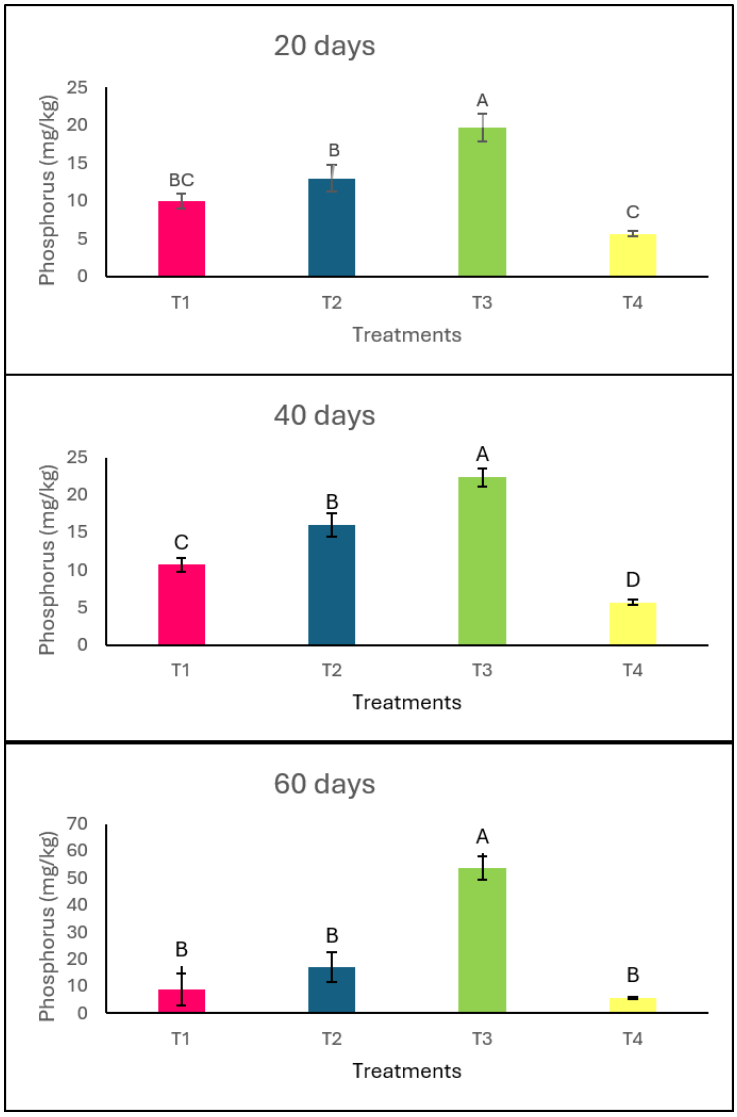

Figure 4. Effect of compost treatments on soil available phosphorus at 20, 40 and 60 days. Bars represent means ± standard error; means sharing the same letter within a sampling date are not significantly different according to Tukey's honestly significant difference test at $p \leq 0.05$.

Comparative Effects of Compost Amendments on Soil Chemical Properties

The amendments displayed distinct functional responses. GML-enhanced compost was the most effective acidity-correcting material and its pH effect was already established by Day 20. Vermicompost produced the greatest late-incubation EC and the highest available K and P, while IMO compost generally produced an intermediate response. These differences are consistent with the measured properties of the finished composts: GML-enhanced compost had the highest pH and a carbonate input, whereas vermicompost had the highest N, P and K concentrations and the narrowest C:N ratio (Table 1).

The marked pH increase under GML-enhanced compost did not translate into the greatest K or P availability because acidity correction and nutrient supply were controlled by different amendment properties. GML directly neutralised acidity but contained less K and P than the biological composts. Vermicompost produced a smaller pH response but contained larger nutrient pools and produced the highest late-incubation EC, available K and available P. These findings indicate that amendment selection should consider the principal soil constraint: GML-enhanced compost for stronger acidity correction and vermicompost where nutrient availability is the greater limitation. Their combined or sequential use warrants further evaluation where both constraints occur.

CONCLUSION

Composting method strongly influenced the chemical response of the *Typic Paleudult* to MD2 pineapple-waste composts. GML-enhanced compost produced the greatest and most stable increase in soil pH, whereas vermicompost produced the highest available K and P and the greatest EC by Day 60. IMO compost generally produced an intermediate response. The results demonstrate that composts produced from the same feedstock can perform different soil-management functions depending on the composting method. Further greenhouse and field studies should evaluate multiple amendment rates, crop nutrient uptake, residual soil fertility and the potential combined use of GML-enhanced compost and vermicompost.

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