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Comparative Study on Composting and Vermicomposting for Digestate Physicochemical Enhancement *via* Kitchen Waste Addition

Running title: Kitchen Waste Addition for Digestate Enhancement

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SUMMARY

Research background. The escalating growth in Malaysian population has resulted in the rise of kitchen waste generation, especially inedible organic kitchen waste, which is generally disposed to landfills and impacts the environment. Apart from that, the increasing demand for chicken products in Malaysia has led to a significant increase in chicken manure production, and with the anaerobic

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digestion being explored further, there is a concern in utilization of the chicken manure digestate. Hence, this research addresses the challenge of treating kitchen waste and chicken manure digestate in Malaysia by exploring the effectiveness of composting and vermicomposting methods via comparative analysis. With the integration of kitchen waste, specifically spent coffee grounds, bone waste, and used kitchen towel, this study aims to enhance the imbalanced physicochemical properties of chicken manure digestate.

Experimental approach. Before composting, characterisation of kitchen waste and chicken manure digestate was performed to investigate the initial physicochemical properties. Four composting setups comprising the substances were established to study the physical appearance, temperature and pH profile, enhancement of nitrogen, phosphorus and potassium content, and the mass reduction in the final compost upon 50-day composting.

Results and conclusions. The vermicompost with kitchen waste additives observed significant nutrient enhancement with an NPK ratio of 1:3.57:6.58 with lower moisture content of 48.92 %, requiring the shortest maturity duration (20 days), and highest mass reduction (55.11 %).

Novelty and scientific contribution. The novelty of this research highlights the valorisation of organic kitchen waste and chicken manure digestate as biofertilizers. The final output is achieved by promoting a sustainable alternative to accommodate kitchen waste besides a conventional waste-to-landfill approach, while addressing the pain point of digestate, primarily its imbalanced physicochemical properties, specifically its macronutrients, pH, and moisture content. In contrast to previous studies, the framework of this work investigates the effectiveness of both conventional composting and vermicomposting with the incorporation of organic kitchen waste, namely spent coffee grounds, bone meals, and used kitchen towels in enhancing the physicochemical properties of digestate.

Keywords: conventional composting; vermicomposting; chicken manure digestate; kitchen waste; physicochemical enhancement; macronutrients enrichment

INTRODUCTION

In Malaysia, kitchen waste concerns have been amplified over the years due to the population growth and Malaysian's food ethics. The daily kitchen waste generation averages 17,007 tons, including 12,926 tons inedible and 4,081 tons edible kitchen waste, while over 90 % of kitchen waste is biodegradable (*1,2*). Kitchen waste is in direct conflict with the objectives set forth in Sustainable

Development Goal (SDG), which seeks to address global food loss and waste through responsible consumption and production of food sources. Regrettably, approx. 80 % of this organic waste ends up in landfills, exacerbating greenhouse gas emissions and posing a threat to soil and groundwater contamination due to leaching of nutrients (*1*). The waste-to-landfill approach results in missed opportunities for value-added components to be harnessed back into the economy, causing greater capital investment to be required for the exploitation of new resources (*3*). Among various types of kitchen waste, spent coffee grounds, bone waste, banana peels, and used kitchen towels are among the organic kitchen waste rich in nitrogen, phosphorus, potassium, and carbon, respectively, representing a mix of inedible and unavoidable materials abundance in Malaysian households with high consumption.

The poultry sector in Malaysia has experienced significant growth over the past few decades, driven by the rising demand for chicken products. In 2022, consumption of chicken meat per capita reached an approx. 50.1 kg, resulting in the daily production of approx. 26,424 tons of chicken manure (*4*). Anaerobic digestion has emerged as a prevalent technology in treating chicken manure due to its high moisture content and biodegradability (*5*). Stripped of oxygen, anaerobic digestion involves hydrolysis of organic matter by microorganisms, followed by acidogenesis and methanogenesis to convert the intermediates into biogas. Despite the low production of biogas volume per batch compared to the huge amount of generated nutrient-rich chicken manure digestate, anaerobic digestion continuously garners significant research attention from academia and industry (*6*). As an underexploited by-product rich in organic and inorganic nutrients, the full potential of chicken manure digestate has yet to be rejuvenated by the agriculture industry. Although direct application of chicken manure digestate as a biofertilizer is an alternative in agriculture to reduce the dependency on synthetic fertilizer (*7*), it is not apt for plant uptake due to its sludgy texture and high MC. This poses the potential for leaching macronutrients such as NPKC, which are specifically crucial for optimal fertilization. This has resulted in the insignificance of nutrient supply for plants, manifesting stunted plant growth, and an overall lacklustre vegetative development (*8-11*).

To enhance the quality and stability of chicken manure digestate as a biofertilizer, composting emerges as an evergreen and economically viable approach for households and the agricultural industry due to its cost-effectiveness and scalability for rejuvenating organic waste (*5,12*). Studies affirm its efficacy in enriching the environment, reducing waste to landfills, mitigating greenhouse gas emissions, and promoting vibrant landscapes (*7,13*). chicken manure digestate can either be composted with other nutrient-rich organic materials, or vermicomposted with the aid of earthworms to enhance the quality of the end product, the compost (*14*). As a subbranch of composting, vermicomposting has gained recognition as an eco-friendly waste management approach, mainly due to its time-saving nature compared to conventional composting (*15*). Vermicompost contains substantial nutrient content (N, P, K, humic and fulvic acid) in plant-accessible forms, improved microbial activity, and enhanced water retention (*15-17*).

Even though the researchers have consistently explored the synergies between chicken manure digestate and other organic inputs to refine the composting process and its physicochemical quality (*16,18*), the formulation of organic kitchen waste and chicken manure digestate has received minimal attention in past studies. Additionally, the comparative analysis between composting and vermicomposting techniques with and without the incorporation of the organic kitchen waste and their effect on improving the physicochemical properties of chicken manure digestate has not been conducted. This study explicitly aims to fill this research gap by systematically comparing composting and vermicomposting as techniques for enhancing chicken manure digestate physicochemical properties. The investigation will focus on the effectiveness of these methods in combination with specific kitchen wastes, such as spent coffee grounds, bone waste, banana peels, and used kitchen towels. By emphasizing the strengths and limitations of each approach, this research highlights their potential for broader application in waste management and agricultural practices.

As these kitchen waste are proven to be biodegradable, they serve as potential texture and nutrient amender for chicken manure digestate via composting method, adding value to the compost produced while facilitating the circular economy model, as discussed by Hashim *et al*. (*1*). Hence, this research focuses on proposing a sustainable alternative for the conventional kitchen waste-to-landfill practice, while addressing the issue of imbalanced physicochemical properties of chicken manure digestateas biofertilizer. It studies the effectiveness of composting and vermicomposting towards physicochemical enhancement of chicken manure digestate with organic kitchen waste as organic additives. Highlighting the ease of execution, this paper also serves as a basis for future commercialization on an industrial scale. This effort aligns with the United Nation Sustainable Development Goals (SDGs) of affordable and clean energy, sustainable cities and communities, responsible consumption and production, and climate action.

MATERIALS AND METHODS

Sample preparation

The chicken manure digestate was acquired from a biogas pilot-scale operation in Manjung district, Perak, Malaysia. A dewatering process was conducted to separate the liquid and solid fractions of the digestate using the Hermle Z513K large volume centrifuge (Hermle, Gosheim, Germany) with a centrifuging speed of 3000 rpm for 40 min per batch. The liquid fraction was kept for the moisturization of compost, while the solid fraction was used as composting material.

Spent Arabica coffee grounds (Soo Hup Seng Trading Co, Penang, Malaysia), Cavendish banana peel (Simple Farm Group, Johor, Malaysia), and used kitchen towels (Premier, Bangalore, India) were collected from the local cafeteria and dried overnight at 105 °C to remove moisture. Waste chicken bones were collected from a local cafeteria in Universiti Teknologi PETRONAS, Seri Iskandar, Perak, Malaysia. Thorough washing was done to remove the residual meat from the bone surface, followed by 6 h of boiling. The boiled bones were dried overnight at 105 °C and ground into a fine powder.

Characterization of organic substances

The raw materials were characterized to determine the physicochemical properties, and the analysis techniques outlined were repeated on compost samples to evaluate the maturity and degree of nutrient enhancement. The Elementar Vario Micro Cube carbon, hydrogen, nitrogen and sulphur analyser (Elementar, Frankfurt, Germany) was utilized to determine the C and N content, requiring 2.5 g of each sample in dried form. The C and N content of the samples were determined through combustion in an oxygen-rich environment, converting the elements into measurable gases, which were quantified using the built-in thermal conductivity detector. The K content of the samples was determined using Shimadzu AA6800 atomic absorption spectroscopy analyser (Shimadzu, Kyoto, Japan). Liquid samples were prepared and diluted accordingly with a dilution factor of 100 to facilitate the vaporization process, as the concentration of K was measured through the absorption of light at a specific wavelength in the presence of K ions. The moisture content of each sample was determined using the Mettler Toledo moisture analyser (Mettler Toledo, Greifensee, Switzerland), which combusted the samples and calculated losses of the moisture content as the mass difference. Hanna Direct Soil Measurement pH portable meter (Hanna Instruments, Woonsocket, USA) was used to determine the pH value of the waste samples and the compost mediums.

The P content was determined using the Hach phosphorus, total - USEPA PhosVer 3 acid persulfate digestion method, otherwise known as method 8190 (*19*) using the Hach DR3900 spectrophotometer (Hach, Ames, USA). A volume of 5 mL of diluted liquid samples was added to the total phosphorus test vials (Hach, Ames, USA), followed by 0.5 g of potassium persulfate powder (Hach, Ames, USA) for each vial. The vials were shaken well before the digestion in DRB200 reactor (Hach, Ames, USA), which was preheated to 150 °C for 30 min. Then the vials were removed from the reactor and cooled to room temperature. A volume of 2 mL of 1.54 N sodium hydroxide standard solution (Hach, Ames, USA) was mixed into each vial, followed by the zeroing of the DR3900 spectrophotometer. A mass of 0.5 g of PhosVer 3 powder (Hach, Ames, USA) was added to each vial and shaken thoroughly until the colour change was observed. After a 2-minute reaction time, the vials were placed back into the spectrophotometer, and the absorbance was read.

Composting and vermicomposting

The required mass of each material was calculated based on the nutrient contents of each raw material for effective composting. The limiting reactant was the chicken manure digestate, as the focus of the study. Hence, the mass of other organic additives should not surpass that of the chicken manure digestate per batch, with the total initial compost mixture set at 1.5 kg. The predicted mass fraction (%) of each nutrient element in the final compost was calculated using the following equation:

$$w(\mathrm{E})=(((m_\mathrm{D}\cdot w(\mathrm{E})_\mathrm{D})+(m_\mathrm{SCG}\cdot w(\mathrm{E})_\mathrm{SCG})+(m_\mathrm{BW}\cdot w(\mathrm{E})_\mathrm{BW})+(m_\mathrm{UKT}\cdot w(\mathrm{E})_\mathrm{UKT}))/(m_\mathrm{D}+m_\mathrm{SCG}+m_\mathrm{BW}+m_\mathrm{UKT}))\cdot 100 \quad /1/$$

where $w(\mathrm{E})$ is the mass fraction of nutrient in the final compost, $w(\mathrm{E})_\mathrm{D}$ is the mass fraction of nutrient element in chicken manure digestate, $w(\mathrm{E})_\mathrm{SCG}$ is the mass fraction of nutrient element of spent coffee grounds, $w(\mathrm{E})_\mathrm{BW}$ is the mass fraction of nutrient element in bone waste, $w(\mathrm{E})_\mathrm{UKT}$ is the mass fraction of nutrient element in used kitchen towels, m_D is the mass of chicken manure digestate, m_SCG is the mass of spent coffee grounds, m_BW is the mass of bone waste, and m_UKT is the mass of used kitchen towels. The compost samples were adjusted to C/N ratio of 10. The C/N of 10 was chosen to ensure a sufficient C supply to be utilized by the bacteria and earthworms as they decompose the organic matter, as well as to regulate the temperature and pH value within the composting system.

The organic materials were mashed into small pieces and mixed well to achieve the ideal particle size range of 5 to 20 cm for enhanced aeration and moisture retention of the composting process (*20*). The composting activity was carried out using four setups of 15 L 19 cm×10.23 cm×22.5 cm covered black plastic containers (Eco-Shop, Kuala Lumpur, Malaysia) with 20 aeration holes. The compost setups were surrounded with green PVC garden netting (Baba Gardening, Penang, Malaysia) to protect from pest invasion. The initial feedstock for each composting setup is shown in

Table S1. For the vermicomposting setups (setup B and D), 100 *Eisenia fetida* earthworms (Earth Worm Enterprise, Perak, Malaysia) were placed in the setup to decompose the organic matter. *Eisenia fetida* is preferred due to its capability to promote a less time-consuming process *via* high consumption and digestion rate of organic substances, while showing greater tolerance towards various environmental conditions with a high reproduction rate (*21*). Gardening soil (Baba Gardening, Penang, Malaysia) was added into the vermicomposting setups with a gardening soil to compost mixture ratio of 1:1, serving as the earthworm bedding.

The moisture content and mass of the initial compost were recorded before the commencement of composting to ensure the moisture level between 45 and 60 % for optimal aerobic conditions, while promoting the growth of microbes (*12,14*). The pH and temperature of each setup were recorded in triplicate at 4:00 pm every second day. This was to ensure the pH value remains within the range of 4.5 to 8.5, and to investigate the temperature progression, which includes mesophilic phase (25 to 40 °C), thermophilic or curing phase (>40 °C), and psychrophilic phase (−10 to 20 °C) (*22-24*). After the readings were taken, the composter was watered with 5 mL of digestate liquid fraction and mixed to ensure adequate aeration and effective aerobic decomposition (*25*). Any physical observation on the pile and earthworms was noted as well.

Physicochemical enhancement of compost

Upon achieving day 50 of the composting process, the physicochemical characteristics of the compost were recorded and evaluated, namely the colour and texture of each compost product, as well as the pH, moisture content, mass yield of compost and nitrogen, phosphorus, potassium and carbon (NPKC) content. The mass yield (%) was then calculated using the following equation (*25*):

$$Y=100-((m_1\cdot(100-w(\mathrm{MC}_1))-m_2\cdot(100-w(\mathrm{MC}_2))/(m_1\cdot(100-w(\mathrm{MC}_1)))\cdot 100 \qquad /2/$$

where m_1 is the mass of the initial compost mixture in kg, m_2 is the final mass of mature compost in kg, $w(\mathrm{MC}_1)$ is the mass fraction of the initial compost mixture, and $w(\mathrm{MC}_2)$ is the mass fraction of the final compost mixture. On the other hand, the relative enrichment (RE/%) of the elements in the final compost was evaluated through systematic comparisons of the NPKC content of the final compost produced from different setups. These comparisons were made using the following equation:

$$\mathrm{RE}=((x_f-x_0)/x_0)\cdot 100 \qquad /3/$$

where x_0 and x_f are the concentrations of elements in feedstock and compost respectively. RE>0 represents the potential enrichment of a particular element, while RE<0 indicates the volatilization loss of the element (*7,25*). One-way analysis of variance (ANOVA) and least significant difference (LSD) were observed when the physicochemical enhancement and RE were significant at $p<0.05$ LSD using Microsoft Excel, version 2019 (Microsoft Corporation, Washington, USA).

RESULTS AND DISCUSSION

Physicochemical properties of organic substance

The initial proposal for incorporating kitchen wastes as organic additives is rooted in comprehensive literature studies indicating the abundance of specific nutrients in the selected kitchen waste. These additives, namely spent coffee grounds for N, bone waste for P, banana peel for K, and used kitchen towels as a C bulking agent, aim to enhance the nutrient profile of chicken manure digestate for use as fertilizer. To validate these propositions, each additive was characterized using various analytical techniques, as shown in Table 1.

While the actual and literature values of C, N and P contents in chicken manure digestate were consistent, a notable variance was observed in K content, which exceeded the literature value by over twofold. This variance may be attributed to the fluctuating K content in the chicken manure used for anaerobic digestion, influenced by nutrient variations in the chicken farm's fodder (*33*). The solubility of K ions in water and the freshness of the digestate samples during testing can also significantly affect the resulting K content (*7,25*).

Based on the results in Table 1, spent coffee grounds exhibited the highest C content (over 50 %), followed by banana peel (41.3 %) and used kitchen towels (39.87 %). In contrast, bone waste emerged as the additive with the highest N content (5.74 %), surpassing spent coffee grounds (4.54 %). C/N ratio, a vital indicator of nutrient balance in composting, was considered, revealing used kitchen towels to retain the highest C/N ratio due to its lower N content. Despite bone waste P content being lower (22.26 %) than the literature value (40.99 %), it remained the additive with the highest P content. Spent coffee grounds contained the most abundant K (6.54 %), followed by banana peel (5.26 %), bone waste (4.55 %), and used kitchen towels (3.14 %). This aligns with previous findings emphasizing spent coffee grounds richness in K compared to other nutrients (*26*). Chicken manure digestate exhibited the highest moisture content, highlighting the importance of incorporating lower-moisture additives to improve the aerobic composting environment (*12*). Spent coffee grounds (highest C and K content), bone waste (highest N and P content), and used kitchen towels (highest C/N ratio) were chosen for enhancing chicken manure digestate nutrients based on characterization results, while banana peels were excluded from the composting.

Variations between the characterization values and literature data were attributed to multiple factors. For instance, the variance in nutrient content in spent coffee grounds may be attributed to the diversity of coffee beans, roasting methods, and brewing techniques before disposal (*26*). The observed variation in bone waste values may result from differences in chicken origin, fodder throughout chicken growth, and bone waste sample preparation methods, leading to N content variations (*34,35*). In the case of banana peels, factors such as types, freshness, and analytical techniques contributed to nutrient level disparities (*30,31*). While no comparisons were available for used kitchen towels due to the lack of previous work, this study establishes a baseline for future research exploring their detailed nutrient content.

Physical observation of composting process

The physical changes in each composting setup were recorded, as outlined in Fig. S1. Four composting setups were established to study the efficiency of composting and vermicomposting, with and without organic kitchen waste additives, towards the NPKC enhancement of chicken manure digestate. Focus was placed on differences in physicochemical properties at 40 and 50 days of composting.

Minimal unpleasant odours were released throughout the composting process, indicating a balanced composting environment with no excessive release of N in the form of ammonia gas. Setup A, consisting solely of chicken manure digestate, transitioned from a highly moist and sludgy texture to a relatively dry pebble-like structure by day 40. No significant changes in appearance or colour and no maggots or nematodes were observed in this setup throughout the composting period.

Setup B, similar to setup A but including earthworms and garden soil, faced issues with earthworms escaping and dying as early as day 2, even after multiple attempts to reset the environment. This experimental control highlights the unsuitability of pure chicken manure digestate for vermicomposting due to its high moisture content (83.04 %), which created anaerobic conditions unfavourable for earthworms. Incorporating carbonaceous bulking agents to improve aeration and moisture balance is essential for effective vermicomposting (*15,17,25*).

Setup C, comprising chicken manure digestate and the selected organic additives (spent coffee grounds, bone waste, used kitchen towels) showed gradual degradation of organic substances, particularly used kitchen towels, which had a distinct appearance throughout the process, as depicted in Fig. S1. Maggots and nematodes were observed in the composting medium, feeding on N-dominant materials from day 30, supported by the pH increase after day 30, as illustrated in Fig. 1 (*25*). Small white spots of undecomposed used kitchen towels were still discernible in the setup during sample collection on day 50. This implies that the composting process for setup C required a longer duration compared to other setups due to the high lignocellulosic components in used kitchen towels (*36*).

Setup D shared a similar composting composition with setup C, but with the addition of earthworms and garden soil. By day 20, minimal visible feedstock, mostly used kitchen towels, remained, and by the end of the process, the compost exhibited a darker, lumpier texture and an earthy smell, signifying vermicasting formation. Towards completion, earthworm activity decreased due to food scarcity, aligning with literature suggesting vermicomposting is significantly faster than conventional composting (*16,17,21,25*).

Temperature and pH profile of composting process

Fig. 1 and Fig. 2 display the pH and temperature profiles, respectively, of each compost setup. Three readings were taken at each sampling day to obtain a mean average for reporting.

Based on Fig. 1, the pH profile exhibited fluctuations primarily attributed to microbial and earthworm activity in consuming and degrading organic matter, with minimal effect by the weather (*15,25*). Setup A, composed solely of chicken manure digestate, started with a higher pH due to its initial N content, stabilizing within the range of 6.0 to 6.5 after day 20. This stabilization signifies organic acid formation from microbial decomposition (*23,36*). Setup B exhibited significant fluctuations in pH before abandonment, primarily due to decomposition of dead earthworms and subsequent protein release, leading to increased alkalinity (*17*).

In setup C (chicken manure digestate with additives), the pH value experienced minimal fluctuation at the acidic region before day 30 due to the slow degradation of C-containing materials such as used kitchen towels, rich in lignocellulosic components, into organic acid and CO_2 gas (*25,37*). A notable pH rise after day 30 indicated protein breakdown and ammonia release, requiring a longer composting period for full maturation (*36*). Nonetheless, the pH for setup C did not achieve stabilization on day 50 during sample collection, suggesting a longer composting period is needed for maturation. The pH profile for setup D followed a similar trend to setup C, yet required shorter time to achieve maturation (20 days), exhibited by the plateau in pH trend upon 20 days due to the aid of earthworms, aligning with the findings of Zhou *et al.* (*16*) and Azis *et al.* (*36*).

Unlike the pH profile, the temperature depicted in Fig. 2 fluctuated within the range of 26 to 36 °C, with no distinct observation of the three characteristic composting phases: the mesophilic phase (25 to 40 °C), thermophilic or curing phase (>40 °C), and psychrophilic phase (−10 to 20 °C). These phases were not observed as the composting setups were placed in a shaded outdoor structure, making temperature only a supplementary indicator of compost maturation, aligning with the study conducted by Shamsuddin *et al.* (*38*). Nonetheless, the temperature range of setup D was relatively higher compared to other setups. This can be attributed to the synergistic heat generation from earthworm and microbial activity, indicating enhanced decomposition (*21*). This aligns with the work done of Hau *et al*. (*25*), where vermicomposting often shows a higher temperature profile compared to composting, while the temperature range remains favourable for the living conditions of earthworms to sustain a complete decomposing activity (*15*).

Physicochemical and nutrient enrichment of compost

Table 2 compares the nutrient enrichment in NPKC content, C/N ratio, and the NPK ratio of each compost setup across 40 and 50 days of composting process, with percentage differences represented as RE in Table 3.

Carbon content decreased across all setups over time due to organic matter decomposition, a typical progression during composting (*15*). In setup D, the presence of earthworms minimized carbon loss between days 40 and 50, indicating rapid decomposition in the preliminary stages. Conversely, setups A and C exhibited a more prolonged C decomposition process (*16,17*). Nitrogen content increased during the first 40 days across all setups, attributed to nitrogen mineralization and ammonification processes, which elevated ammonia levels in the early composting stage (*39*). However, nitrogen levels decreased between days 40 and 50 in setups A and D, likely due to nitrogen loss during formation of oxides or compost stabilization, consistent with the increasing trends in the C/N ratio (*15*). The observation was further supported by the one-way ANOVA results for C/N ratio between setup A and D at day 50 of composting. While a lower C/N ratio suggests compost maturity, the ratio tends to stabilize within the optimal range of 10:1 to 15:1 through nitrogen release, aligning with previous studies (*24,25,27*).

Phosphorus content increased across all setups, with vermicomposting (setup D) showing the most significant enhancement due to phosphorus-solubilizing microorganisms and the conversion of organic phosphorus into plant-available inorganic forms as organic matter passed through earthworm guts (*40*). Similarly, potassium content increased in all setups, with vermicompost achieving the highest levels due to high microbial activity that solubilized insoluble potassium compounds (*24*). These findings were strengthened by the one-way ANOVA results, which show that setup D was significantly different from setups A and C upon 50 days of composting.

Comparing the initial NPK ratio of fresh chicken manure digestate (2.35:1:2.45), all compost setups exhibited lower nitrogen proportions but significantly higher phosphorus and potassium ratios, especially in the vermicompost setup (1:3.57:6.58). This enhancement in NPK content during vermicomposting was attributed to nutrient mineralization, with previous studies emphasizing the slow-release nature of nutrients in vermicompost, reducing environmental pollution from nutrient leaching (*20,41*).

The mass yield and moisture content of the final compost product from each setup are summarized in Table 4. All setups experienced mass reductions, with setup A showing the least due to its high moisture content, which created anaerobic conditions unfavourable for microbial activity (*25*). In contrast, setup C exhibited faster organic matter decomposition due to its healthier aerobic conditions and higher initial nitrogen-to-carbon ratio, which resulted in greater mass loss (*27*). Setup D showed the greatest mass reduction, attributed to the synergistic effects of earthworms and microorganisms as strong decomposers, breaking down rigid carbon-rich materials and grinding waste, resulting in greater mass reduction compared to setup A (*21*).

CONCLUSIONS

Characterization of organic additives, including spent coffee grounds, bone waste, banana peels and used kitchen towels, was conducted, with spent coffee grounds showing the highest carbon (50.05 %) and potassium (6.54 %) content, bone waste the highest nitrogen (5.74 %) and phosphorus (22.26 %) content, and used kitchen towels the highest C/N ratio (15.51:1). Comprehensive analysis among the four composting and vermicomposting setups revealed that the vermicomposting setup with organic additives (setup D) has exhibited the highest nutrient enhancement of the NPK ratio (1:3.57:6.58) at day 50 from the initial NPK ratio of 2.35:1:2.45 for chicken manure digestate. Notably, setup D achieved maturity in the shortest composting duration (20 days), with a significant mass reduction of 54.22 % from the initial feedstock. These findings underscore the effectiveness of vermicomposting with organic kitchen waste in enhancing the physicochemical properties of chicken manure digestate, while achieving substantial mass reduction of organic waste at a reduced composting time. Multiple SDGs have been reached by promoting circular economy with a cost-effective and easy-to-execute solution of vermicomposting for organic waste management with considerable environmental and economic benefits.

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CONFLICT OF INTEREST

The authors declare that they have no conflicting interest.

SUPPLEMENTARY MATERIALS

Supplementary materials are available at: www.ftb.com.hr.

AUTHORS' CONTRIBUTION

Ze Sen Tan contributed to the conceptualization and design of the work, data collection, data analysis and interpretation, performing the analysis, drafting the article, critical revision. M.Devendran Manogaran contributed to the conceptualization and design of the work, data analysis and interpretation, critical revision, and final approval prior publication. Rashid Shamsuddin contributed to the conceptualization and design of the work, validation of analysis, project administration, supervision, critical revision, and final approval prior publication. Both Mohd Hakimi and Lee Wen Looi were involved in data analysis and interpretation, as well as critical revision. Kai Tong Woo involved in critical revision. Chin Seng Liew involved in conceptualization and critical revision, while Lailatul Qomariyah involved in critical revision.

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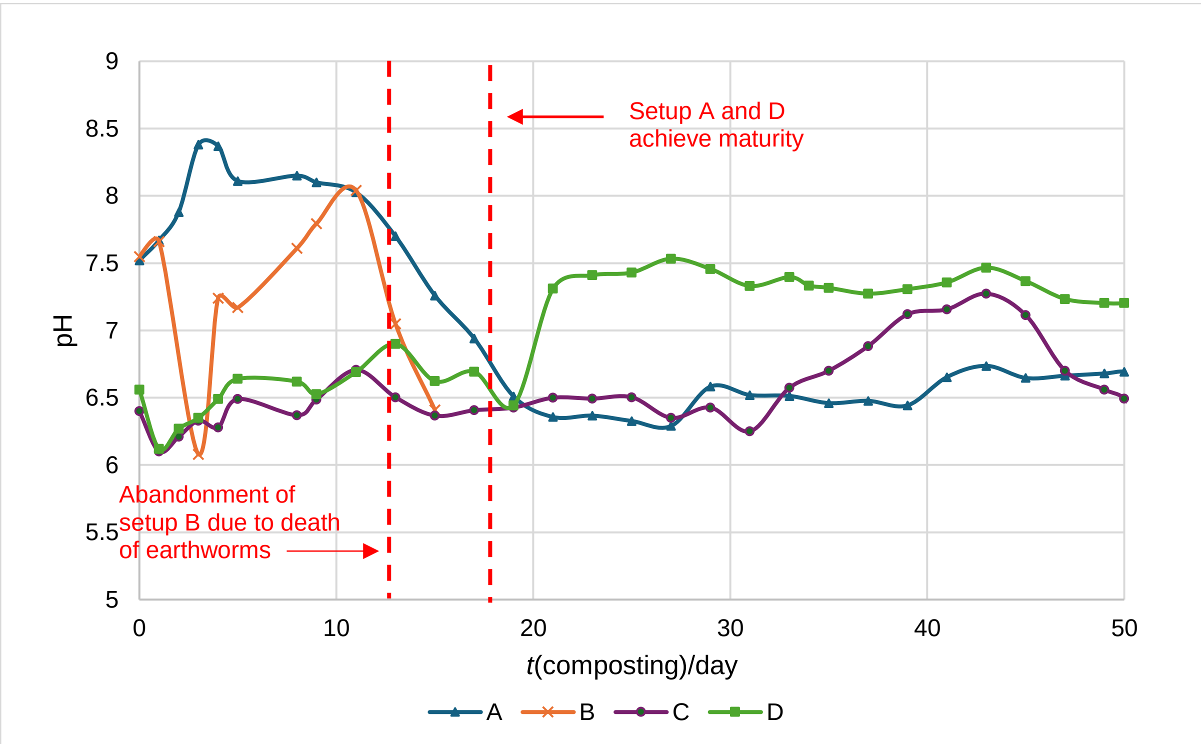


Fig. 1. pH profile of compost setups over 50 days of composting. pH measurements are average of three readings

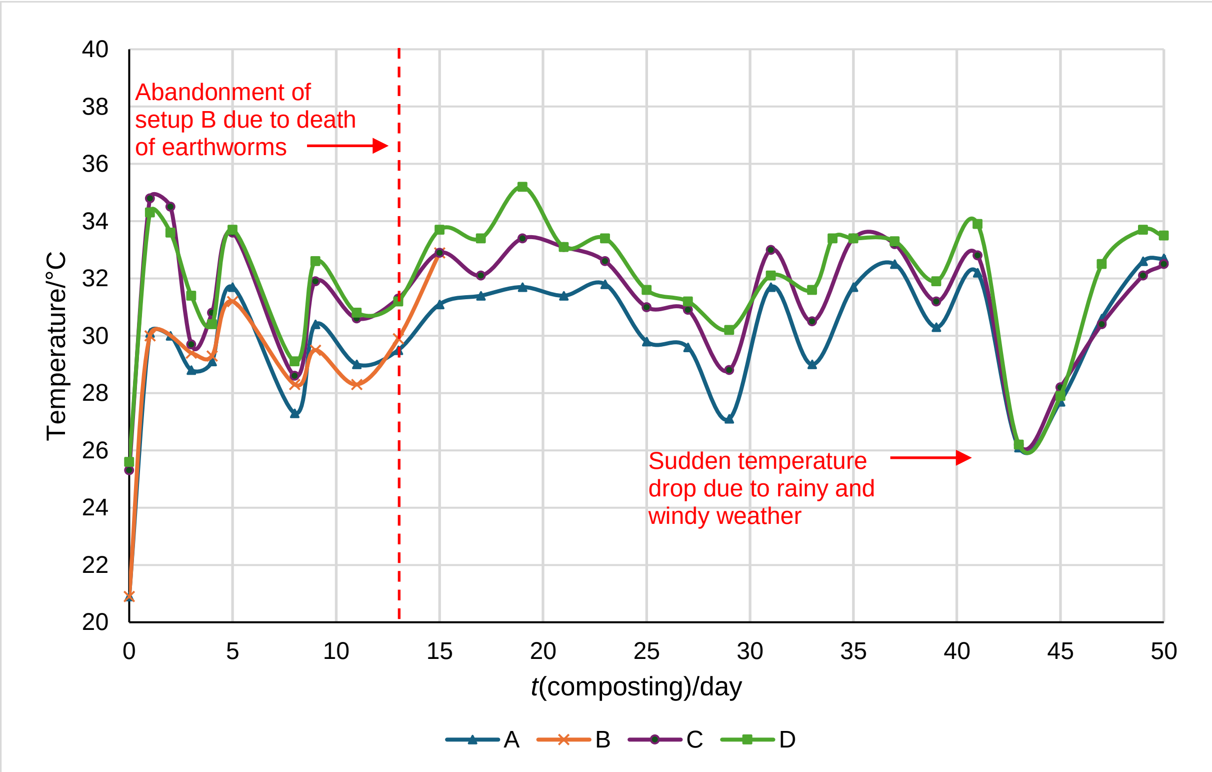


Fig. 2. Temperature profile of compost setups over 50 days of composting. Temperature measurements were average of three readings

Table 1. Physicochemical properties of the organic substances

Property		Chicken manure digestate	Spent coffee grounds	Bone waste	Banana peels	Used kitchen towels
w(C)/%	C_A	(34.98±1.19)	(50.03±0.60)	(33.32±2.73)	(41.30±0.69)	(39.87±0.13)
	C_L	36.01 (*7*)	46.24 (*26*)	43.08 (*28*)	43.71 (*30*)	N/A
w(N)/%	N_A	(4.87±0.08)	(4.54±0.05)	(5.74±0.26)	(3.27±0.07)	(2.57±0.02)
	N_L	4.52 (*7*)	2.37 (*26*)	15.7 (*28*)	1.46 (*30*)	N/A
C/N ratio	C/N_A	(7.18±0.21)	(11.02±0.20)	(5.80±0.31)	(11.90±0.13)	(15.51±0.10)
	C/N_L	7.97 (*7*)	19.51 (*26*)	22.26 (*28*)	29.94 (*30*)	N/A
w(P)/%	P_A	(2.07±0.25)	(2.53±0.19)	(22.26±0.03)	(1.40±0.08)	(0.39±0.11)
	P_L	1.68 (*7*)	0.89 (*26*)	40.99 (*28*)	1.60 (*30*)	N/A
w(K)/%	K_A	(5.08±0.14)	(6.54±0.06)	(4.55±0.13)	(5.26±0.08)	(1.43±0.12)
	K_L	2.12 (*7*)	3.72 (*26*)	0.03 (*28*)	7.81 (*31*)	N/A
w(moisture)/%	MC_A	(83.04±0.91)	(62.31±1.09)	(7.73±0.32)	(10.92±0.54)	(66.98±0.67)
	MC_L	67.48 (*12*)	61.00 (*27*)	63.79 (*29*)	89.09 (*32*)	N/A

Literature values are not presented with standard deviation. X_A=elemental composition obtained through characterization, X_L=elemental composition obtained from literature study. Results are expressed as mean value±standard deviation, *N*=3

Table 2. Nutrient enrichment of compost setup over 40 days and 50 days of composting

Nutrient element		Setup A	Setup C	Setup D
	C_0	(34.98±1.19)[a]	(43.96±0.61)[b]	(21.71±0.61)[c]
w(C)/%	C_{40}	(34.67±3.55)[a]	(38.98±1.93)[a]	(16.46±2.67)[b]
	C_{50}	(32.14±0.80)[a]	(32.86±1.52)[a]	(17.35±1.62)[b]
	N_0	(4.87±0.08)[a]	(4.93±1.02)[a]	(2.15±0.10)[b]
w(N)/%	N_{40}	(5.40±0.20)[a]	(6.52±0.31)[b]	(4.36±0.16)[c]
	N_{50}	(2.48±0.09)[a]	(3.94±0.18)[b]	(1.50±0.27)[c]
	C_0/N_0	(7.18±0.21)[a]	(8.92±2.19)[ab]	(10.11±0.40)[b]
C/N ratio	C_{40}/N_{40}	(6.42±0.50)[a]	(5.98±0.28)[a]	(3.25±0.50)[b]
	C_{50}/N_{50}	(12.96±0.96)[a]	(8.35±0.17)[b]	(12.65±0.75)[a]
	P_0	(2.07±0.25)[a]	(1.75±0.04)[b]	(2.38±0.07)[c]
w(P)/%	P_{40}	(2.97±0.04)[a]	(1.52±0.04)[b]	(2.70±0.07)[c]
	P_{50}	(3.98±0.05)[a]	(4.75±0.26)[b]	(5.36±0.04)[c]
	K_0	(5.08±0.14)[a]	(4.57±0.31)[b]	(5.03±0.10)[a]
w(K)/%	K_{40}	(5.26±0.19)[a]	(5.96±0.30)[b]	(6.35±0.31)[b]
	K_{50}	(6.83±1.16)[a]	(8.33±1.06)[a]	(9.87±0.65)[b]
	D_0	2.35:1:2.45	2.82:1:2.70	1:1.11:2.50
NPK ratio	D_{40}	1.82:1:1.77	4.29:1:3.92	1.61:1:2.35
	D_{50}	1:1.60:2.75	1:1.20:2.11	1:3.57:6.58

X_{40}=elemental composition at 40-days composting, X_{50}=elemental composition at 50-days composting. Mean values across the same row with different superscript letter differ significantly ($p<0.05$). Results are expressed as mean value±standard deviation, *N*=3

Table 3. Relative enrichment (RE) of NPKC content after composting

Nutrient element		Setup A	Setup C	Setup D
w(C)/%	RE,C_{40}	-0.89	-11.33	-24.18
	RE,C_{50}	-8.12	-25.25	-20.08
w(N)/%	RE,N_{40}	10.88	32.25	-102.79
	RE,N_{50}	-49.07	-20.08	-30.23
C/N ratio	RE,C_{40}/N_{40}	-10.58	-32.96	-67.85
	RE,C_{50}/N_{50}	80.50	-6.39	25.12
w(P)/%	RE,P_{40}	43.48	-13.14	13.44
	RE,P_{50}	92.27	171.43	125.21
w(K)/%	RE,K_{40}	3.54	30.42	26.24
	RE,K_{50}	34.35	82.27	96.22

Positive and negative signs of RE represent the increment and decrement, respectively, in specific elemental composition upon composting

Table 4. Mass yield, initial and final moisture content of each compost setup

Compost	m_{final}/kg	m_2/kg	MC_1/%	MC_2/%	*Y*/%	$m_{reduction}$/%
A	0.71	0.71	$(83.04\pm0.27)^a$	$(67.12\pm0.37)^a$	91.76	8.23
C	0.63	0.63	$(68.02\pm0.11)^b$	$(67.56\pm0.15)^a$	48.01	51.99
D	2.33	0.83	$(46.14\pm0.18)^c$	$(48.92\pm0.74)^b$	44.89	55.11

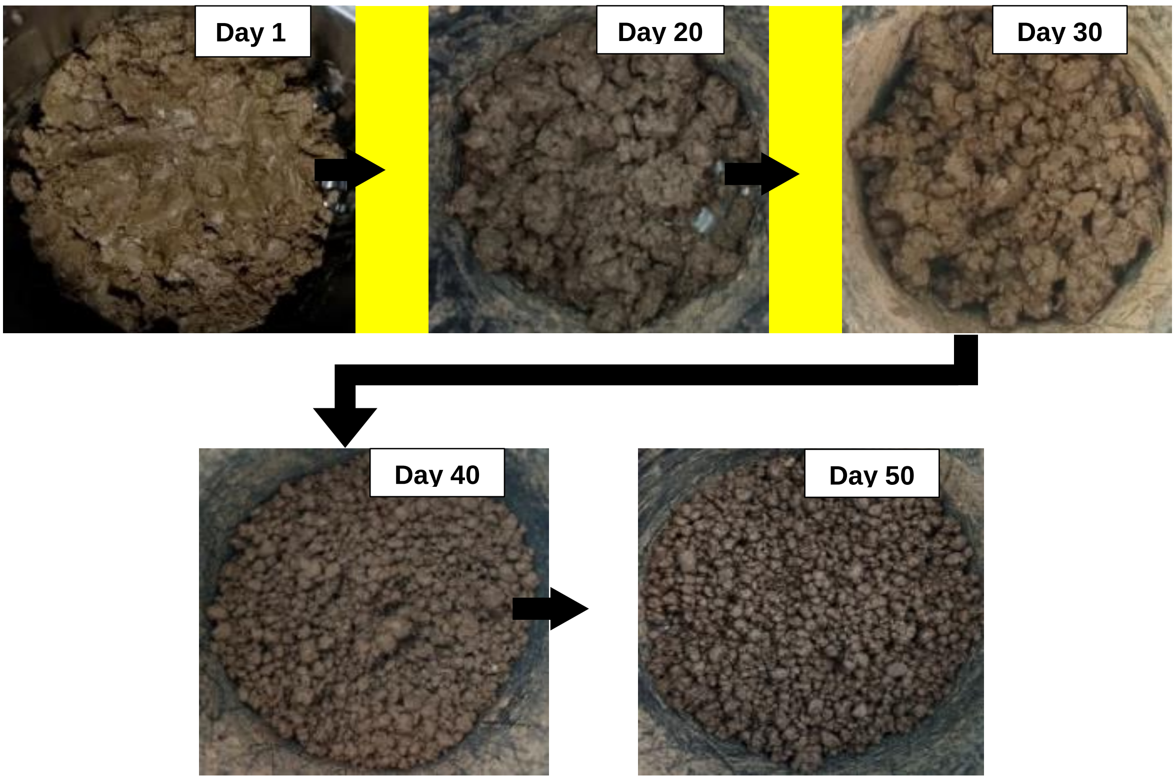
Both mass of soil, *m*(soil)/kg, and initial mass of compost, m_1, are 1.5 kg. m_{final} is the final mass of the compost (including gardening soil). Mean values across the same column with different superscript letters differ significantly ($p<0.05$). Results are expressed as mean value ± standard deviation, N=3

SUPPLEMENTARY MATERIAL

Table S1. Composition of compost setups

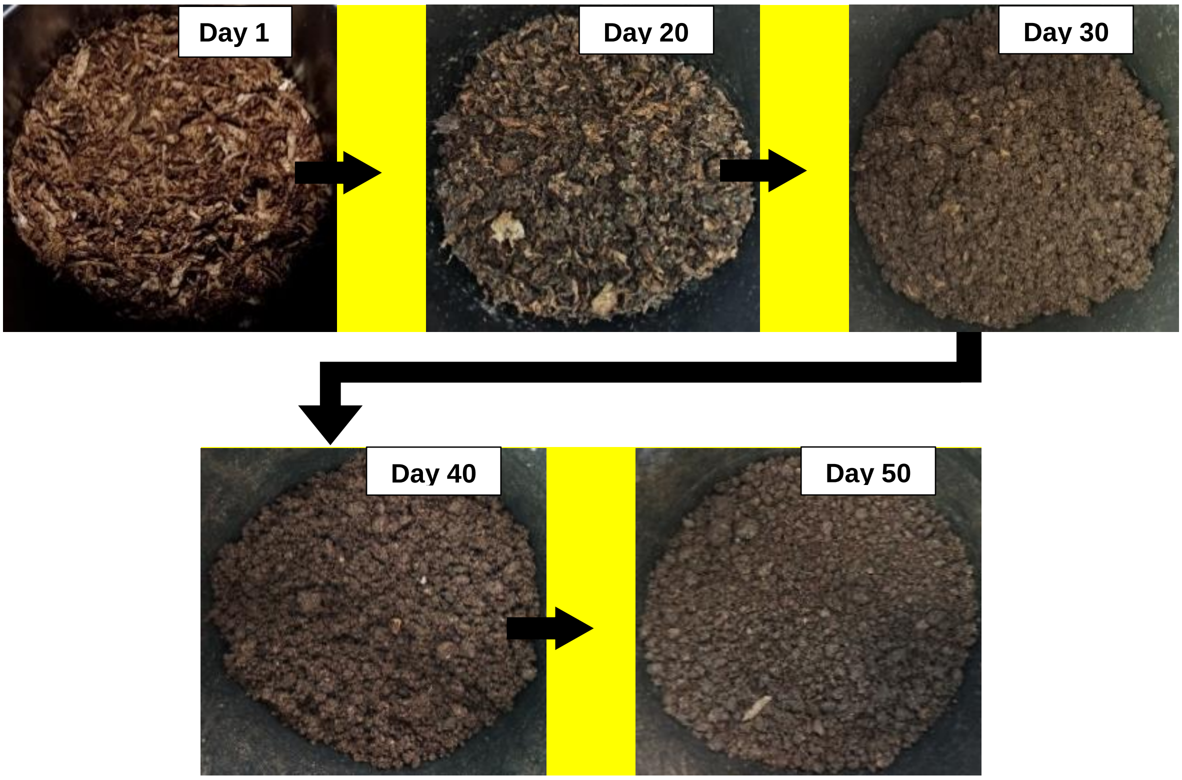
Batch	*m*/kg			
	Chicken manure digestate	Spent coffee grounds	Bone waste	Used kitchen towels
A	1.50	-	-	-
B	1.50	-	-	-
C	0.50	0.40	0.05	0.45
D	0.50	0.40	0.05	0.45

a)



b)

c)



d)

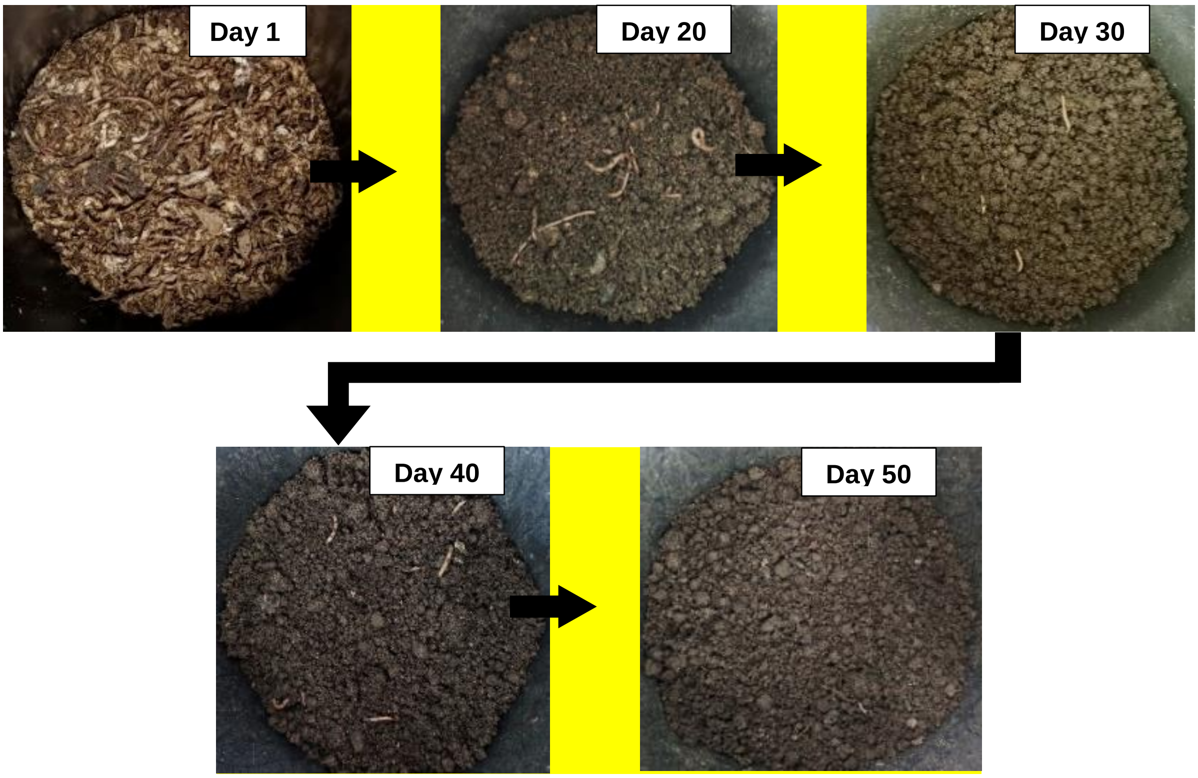


Fig. S1. Physical observations of: a) setup A across the 50-day composting duration, b) setup B across 20 days of composting (setup was abandoned after 20 days due to death of earthworms), c) setup C across 50-day composting duration, and d) setup D across 50-day composting duration