

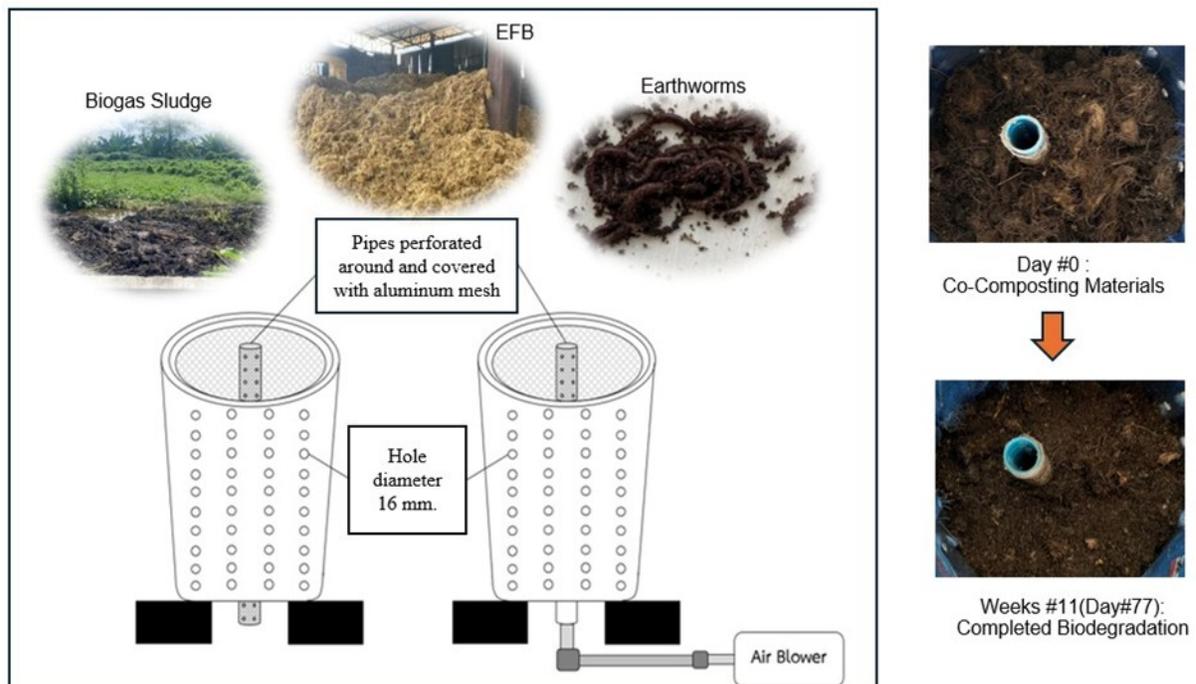
# Aerobic Composting of Palm Oil Mill Biogas Sludge and Empty Fruit Bunches Using Earthworms and a Compost Accelerator

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## GRAPHICAL ABSTRACT



# Aerobic Composting of Palm Oil Mill Biogas Sludge and Empty Fruit Bunches Using Earthworms and a Compost Accelerator

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Aerobic composting was evaluated in the case of palm oil mill biogas sludge mixed with shredded empty fruit bunches (EFB). The decomposers used in the process include microorganisms from the composting materials, earthworms and a compost accelerator. The experiment was conducted using seven reactors. Reactors 1, 2, and 3 used 100% biogas sludge, while reactors 4, 5, 6, and 7 used a mixture of 50% biogas sludge and 50% shredded EFB. Reactor 1 relied on natural aeration, whereas reactors 2 to 7 were supplied with air using a blower at a rate of 0.7 L/min·kg. Earthworms were added to reactors 3 and 5, the accelerator was added to reactor 6, and both earthworms and the accelerator were added to reactor 7. The composting process was carried out over a period of 77 days. Parameters analyzed included temperature, pH, electrical conductivity, moisture content, organic carbon, organic matter, C/N ratio, total nitrogen, total phosphorus, total potassium, particle size, and germination index. The results showed that most parameters in all reactors met the 2014 organic fertilizer standards of the Department of Agriculture (Thailand), with the exception of moisture content and organic matter. Reactor 7 produced compost with the highest nutrient content and a germination index of  $201.46 \pm 6.28\%$ . The compost from reactor 7 was crumbly, black in color, and had an earthy odor.

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## INTRODUCTION

Currently, the management of sludge from biogas systems usually involves dredging once a year, which incurs high costs and also requires space to accommodate the sludge. According to a study by Mustamu and Triyanto (2020), the preliminary characteristics of sludge (semisolid) from biogas systems in crude palm oil extraction plants were investigated. The study found that the sludge is an organic substance with high moisture content and still contains essential plant nutrients, including total nitrogen at 346 mg/L, total phosphorus at 80.0 mg/L, and potassium at 0.90%. It also contains secondary nutrients such as calcium (Ca) at 0.02%, magnesium (Mg) at 0.03%, sodium (Na) at 2.36 mg/L, and copper (Cu) at 0.44 mg/L. These properties indicate that the biogas-sludge, which is a waste product, still contains nutrients beneficial for plant growth and can be reused in agriculture. This represents a sustainable waste management approach.

Furthermore, when sludge is left to accumulate in storage ponds, anaerobic microorganisms decompose it, generating methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>), both of which are greenhouse gases. Methane has a global warming potential 28 to 36 times greater than carbon dioxide (Riddick *et al.* 2019).

Composting technology is an effective method for treating organic waste, producing a stable product that can be used as a soil conditioner. During the composting process, most carbon is transformed into organic matter, and only a small amount is released as CO<sub>2</sub>, making it a method that helps reduce greenhouse net gas emissions (He *et al.* 2000; Kumar *et al.* 2010). Composting involves the decomposition of organic matter driven by physical, chemical, and biological factors (Białobrzewski *et al.* 2015; Onursal and Ekinci 2016). Aerobic microorganisms play a key role in breaking down organic waste into stable organic matter, which is resistant to further decomposition. The final compost is soft, crumbly, easily separable, and has a temperature close to ambient temperature. It is ideal for soil improvement, as it enhances soil structure, increases water retention, and provides both primary and secondary nutrients needed for plant growth.

Organic waste treatment can be divided into two processes; (1) aerobic composting, and (2) anaerobic digesting. Aerobic composting is more commonly used because of its shorter processing time. Additionally, anaerobic composting yields compost with lower nitrogen content (Food and Agriculture Organization 2021). Aeration can be done through natural airflow or using aeration equipment. Mechanical aeration is suitable for fine or highly moist compost materials, where natural airflow is limited due to smaller air gaps. In addition, other decomposing agents can be used in the composting process to enhance decomposition efficiency, including earthworms and compost accelerator. Previous studies have used earthworm species such as *Eisenia fetida* and *Eudrilus eugeniae* as co-decomposers, resulting in compost with higher nutrient content compared to aerobic composting alone (Soobhany *et al.* 2015). Moreover, this method is a type of low-cost biological degradation process (Liew *et al.* 2022). Super LDD 1, the compost accelerator used in the present work, is a selected group of microorganisms with high efficiency in decomposing agricultural waste materials. It consists of bacteria, actinomycetes, and fungi, which are sourced from the Land Development Department. Therefore, this study utilized sludge from a biogas system for compost production in agricultural applications.

## EXPERIMENTAL

This study used sludge from a biogas system and shredded empty fruit bunches (EFB) generated from a crude palm oil extraction plant, as raw materials for aerobic composting in reactors. The composting was conducted using both natural aeration and aeration with an air blower. The decomposition agents used in the experiment included natural microorganisms from the compost materials, earthworms, and the "Super LDD 1" microbial activator.

### Raw Materials

#### *Sludge from the biogas system*

The biogas sludge used in this experiment was provided by a crude palm oil extraction plant located in Surat Thani Province, which employs a wet extraction process. This process produces approximately 400 m<sup>3</sup>/day of wastewater, with suspended solids around 22,000 mg/L and a high COD (Chemical Oxygen Demand). The plant treats its

wastewater using a covered lagoon system with a capacity of 7,200 m<sup>3</sup>. The sludge used for composting was collected from the final effluent pond, where approximately 60 tons/day (wet weight) of sludge is generated. The plant dredges the sludge from the pond and stores it in a concrete pit about once every three months. This operation is costly and challenging during the rainy season. When the storage pond is full, the sludge is transported and applied to the plant's oil palm plantation. The sludge has a semi-solid, semi-liquid texture and a dark black color.

#### *Shredded empty fruit bunches (EFB)*

The shredded EFB used as co-composting material in this study was also provided by the same palm oil extraction plant. It is fibrous, has low moisture content, and contains a high amount of total K<sub>2</sub>O. Normally, the plant uses shredded EFB as boiler fuel and for sale.

### **Decomposition Agents**

#### *Microorganisms from composting materials*

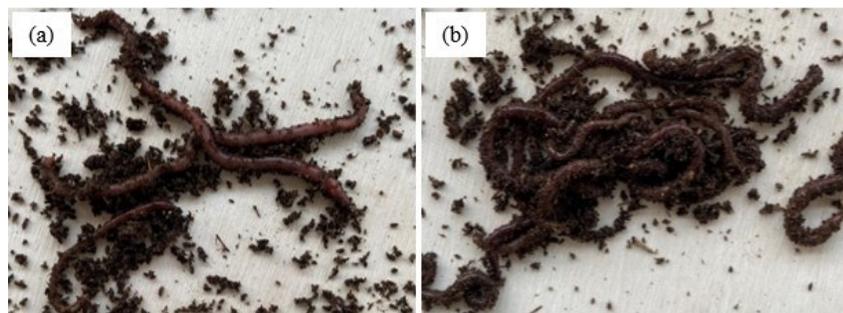
Organic matter is generally biodegradable through the activity of microorganisms that are naturally present in the materials themselves. These microorganisms, present in the composting materials, are capable of decomposing the materials into a compost.

#### *Microbial activator*

About 5.0 g of microbial activator, namely super LDD1, (obtained from the Land Development Department, Thailand), was mixed with 100 mL of distilled water, was added to reactors 6 and 7, and applied once per week. The microbial activator (Super LDD 1) was manufactured by the Department of Land Development, Thailand, and is distributed free of charge to agriculturists for compost production. It consists of microorganisms capable of degrading cellulose, lipids, and lignin, thereby reducing the decomposition time during the composting process (Land Development Department of Thailand 2025; Jaipakdee *et al.* 2025).

#### *Earthworms*

Two species of earthworms were used in the experiment: Tiger Worm (*Eisenia fetida*) and African Nightcrawler (*Eudrilus eugeniae*) (Figs. 1a and 1b). These were kindly provided by Booncharoen Farm in Surat Thani Province. *Eisenia fetida* and *Eudrilus eugeniae* were added at a ratio of 1:1, with 100 g of each species.

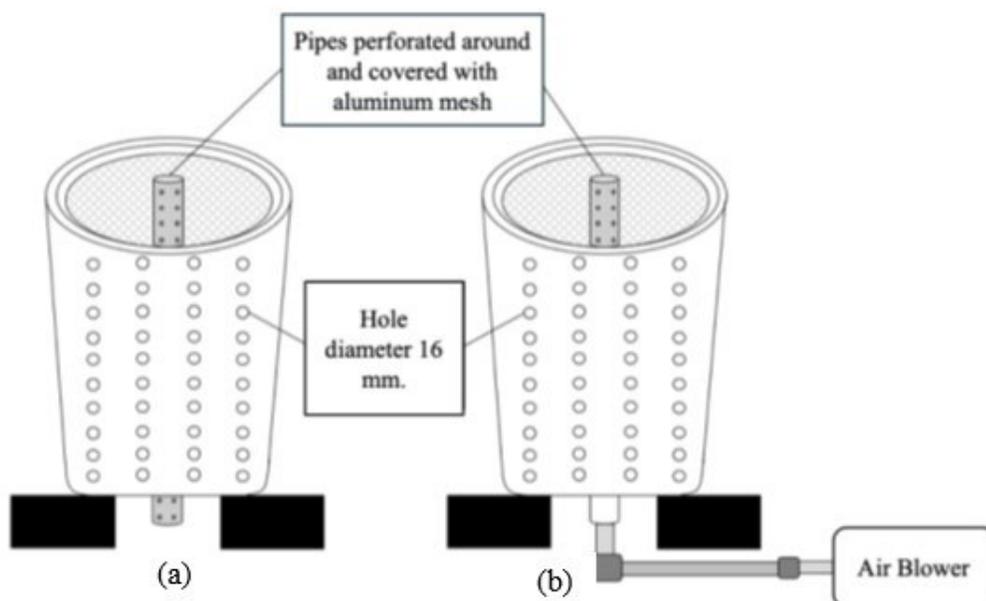


**Fig. 1.** Earthworms (a) *Eisenia fetida* (b) *Eudrilus eugeniae*

For the reactors with added earthworms (reactors 3, 5, and 7), 1 kg of dried cow manure was added to each to create suitable conditions for the earthworms to thrive. The cow manure and earthworms were introduced simultaneously in week 6 of the experiment (after either the thermophilic phase or reduction in the C/N ratio). Water was added every two days to maintain appropriate moisture levels.

### Reactors

The composting reactors were 66-L plastic containers. Each reactor was perforated with 160 holes around the sides, with each hole having a diameter of 16 mm to allow natural air (20% oxygen) to enter the system. Each reactor was also equipped with a perforated pipe wrapped in aluminum mesh to prevent clogging from composting materials. There were two types of reactors used; (1) Reactors with natural aeration, and (2) Reactors with forced aeration using an air blower, as shown in Figs. 2a and 2b.



**Fig. 2.** Composting reactors used in the experiment (a) Reactor with natural aeration (b) Reactor with forced aeration using an air blower

### Composting

This study involved producing compost from biogas sludge generated by a covered lagoon wastewater treatment system at a crude palm oil extraction plant. Shredded empty fruit bunches (EFB) were used as a co-composting material. The experiment was conducted at a laboratory scale using seven reactor setups.

Each reactor contained 50 L of composting material, and the composting process was carried out over a period of 11 weeks (77 days). The physical and chemical characteristics of the compost were examined, including color, odor, appearance of the composting materials, presence of living organisms in the compost, and various analytical parameters. Details of the experimental setup are shown in Table 1.

**Table 1.** Experimental Setup Details

Reactors	Composting Materials	Decomposing Agents	Aeration Methods
R1	100% Biogas Sludge	Indigenous microorganisms from composting materials	Natural Aeration
R2	100% Biogas Sludge	Indigenous microorganisms from composting materials	Forced Aeration (0.7 L/min·kg)
R3	100% Biogas Sludge	Indigenous microorganisms from composting materials + Earthworms	Forced Aeration (0.7 L/min·kg)
R4	50% Biogas Sludge + 50% Shredded EFB	Indigenous microorganisms from composting materials	Forced Aeration (0.7 L/min·kg)
R5	50% Biogas Sludge + 50% EFB	Indigenous microorganisms from composting materials + Earthworms	Forced Aeration (0.7 L/min·kg)
R6	50% Biogas sludge + 50% EFB	Indigenous microorganisms from composting materials + microbial activator	Forced Aeration (0.7 L/min·kg)
R7	50% Biogas sludge + 50% EFB	Indigenous microorganisms from composting materials + microbial activator + Earthworms	Forced Aeration (0.7 L/min·kg)

Note: Earthworms and dried cow manure were added after the thermophilic phase (Week 6). microbial activator composts of four species of cellulolytic fungi, two species of cellulolytic actinomycetes, and two species of lipid-degrading bacteria.

### Parameters analyzed

The analysis of composting parameters and related details is presented in Tables 2 and 3. The parameters were divided into two parts:

(1) Conducted at the Science Project Laboratory 2, Prince of Songkla University, Surat Thani Campus, including temperature, pH, moisture content (MC), electrical conductivity (EC), organic carbon (OC), organic matter (OM), total nitrogen (TN), C/N ratio, particle size, and germination index (GI).

(2) Samples were analyzed at the Central Laboratory, Faculty of Natural Resources, Prince of Songkla University, Hat Yai Campus, for phosphorus content (total P<sub>2</sub>O<sub>5</sub>) and potassium content (total K<sub>2</sub>O).

The germination index (GI) was tested using a compost extract in a 1:10 (weight/volume) ratio and compared to the results with distilled water. Seeds were germinated in both solutions for 48 h in a dark incubator at a controlled temperature of 28 to 30 °C. Afterward, germination percentage and root length were measured according to the method by the Department of Agriculture (2008) using Eqs. 1 to 3:

$$GI (\%) = RSG (\%) \times RRG (\%) / 100 \quad (1)$$

$$RSG (\%) = (N_{com} / N_{con}) \times 100 \quad (2)$$

$$RRG (\%) = (M_{com} / M_{con}) \times 100 \quad (3)$$

where *RSG* is the relative see germination (%), *N<sub>com</sub>* is the number of seeds germinated in compost extract, *N<sub>con</sub>* is the number of seeds germinated in the control, *RRG* is the relative root growth (%), *M<sub>com</sub>* in the mean root length with compost extract, and *M<sub>con</sub>* is the mean root length for the control.

**Table 2.** Parameters and Analytical Details

Parameter	Analytical Method	Materials/Tools
1) Temperature	- Thermometer	- Thermometer
2) pH	- pH Meter	- Bench-top pH Meter Model pH700, Brand: EUTECH - HQ/HQD Series Meter with Intellical Probe, Brand: Hach
3) Moisture Content	- Drying Method	- Hot Air Oven, Brand: Memmert UF 110 Desiccator 4-Digit Balance
4) Electrical Conductivity	- Conductivity Meter	- Portable Conductivity Meter HQ Series, Brand: Hach - HQ/HQD Series Meter with Intellical Probe, Brand: Hach
5) Organic Carbon 6) Organic Matter	- Walkley and Black Method	- Hot Air Oven, Brand: Memmert UF 110 - Fume Hood
7) C/N Ratio	- Calculation	-
8) Total Nitrogen	- Kjeldahl Method	- Kjeldahl Distillation Set
9) Particle Size	- Dry Screen Analysis	- Sieve Set
10) Compost Maturity (Decomposition Completion)	- Germination Index	- Plant Seeds - Plate - Incubator - Shaker
11) Total P <sub>2</sub> O <sub>5</sub>	- Vanadomolybdate Method	- UV-Spectrophotometer - Hot plate
12) Total K <sub>2</sub> O	- Atomic Absorption Spectrophotometer	- Atomic Absorption Spectrophotometer

**Table 3.** Frequency of Parameter Analysis During the Composting Process

Parameter	Frequency
1) pH	Daily
2) Temperature	Daily
3) Electrical conductivity	Daily
4) Moisture content	Once per week
5) C/N Raito	Once per week
6) Organic carbon	Once per week
7) Organic matter	Once per week
8) Total Nitrogen	Once per week
9) Total P <sub>2</sub> O <sub>5</sub>	At the start and end of composting
10) Total K <sub>2</sub> O	At the start and end of composting
11) Particle size	At the end of composting
12) Germination index	At the end of composting
13) Plastics, Glass, Sharp Materials, and Metals	At the end of composting

### Statistical analysis

Analytical statistical testing was conducted using Microsoft Excel to calculate the mean, maximum, minimum, sum, and standard deviation. In addition, Statistical analyses were conducted using Microsoft Excel (Data Analysis ToolPak). One-way analysis of variance (ANOVA, single factor) was used to determine statistically significant differences among composting reactors (R1 to R7). When significant differences were detected, pairwise comparisons between reactors were performed using two-tailed post hoc Student's t-tests with Bonferroni correction. The adjusted significance level was set at  $\alpha_{\text{adjust}} = \alpha/m = 0.05/21 = 0.00238$ , where  $m=21$  is the number of pair comparison.

## RESULTS AND DISCUSSION

This research involved producing aerobic compost from biogas sludge obtained from the wastewater treatment system of a crude palm oil extraction factory. A total of seven experimental setups were conducted. After six weeks, earthworms (two species: *Eudrilus eugeniae* and *Eisenia fetida*) were added to reactors 3, 5, and 7 at a 1:1 ratio by weight. The total composting period was 11 weeks. The findings of the study are summarized as follows:

### Properties of Composting Materials

The aerobic composting process used two primary composting materials: biogas sludge and shredded EFB. Preliminary analyses included pH, electrical conductivity (EC), moisture content (MC), organic carbon (OC), carbon-to-nitrogen ratio (C/N), nitrogen, phosphorus, and potassium. The results showed that the pH of the biogas sludge was  $8.30 \pm 0.03$ , indicating a slightly alkaline nature. The shredded EFB had a pH of  $4.77 \pm 0.03$ , which is acidic, while cow dung (used in reactors 3, 5, and 7) had a pH of  $7.10 \pm 0.02$ , suitable for earthworm activity. The total nitrogen content of the biogas sludge and shredded EFB was 0.86% and 1.24%, respectively. The total  $K_2O$  content in the biogas sludge was  $1.26 \pm 0.01\%$ , slightly lower than the  $1.72 \pm 0.10\%$  reported by Nutongkaew *et al.* (2011). The results of other analyzed parameters are shown in Table 4.

**Table 4.** Properties of Composting Materials

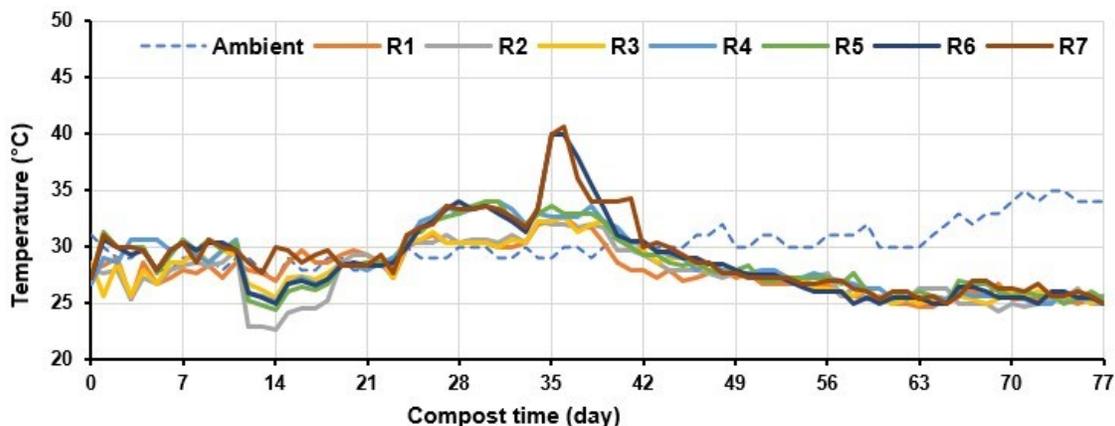
Parameter	Biogas sludge	Shredded empty fruit bunch	Cow dung	Biogas sludge Nutongkaew <i>et al.</i> 2011
pH	$8.30 \pm 0.03$	$4.77 \pm 0.03$	$7.10 \pm 0.02$	8.41
EC (dS/m)	$2.85 \pm 0.15$	$2.94 \pm 0.02$	$2.40 \pm 0.02$	-
Moisture Content (%)	$34.12 \pm 5.53$	$44.45 \pm 1.88$	$29.72 \pm 3.16$	-
Organic Matter (%)	$15.47 \pm 3.38$	$20.30 \pm 1.31$	$44.93 \pm 0.90$	$36.06 \pm 0.03$
Organic Carbon (%)	$8.97 \pm 1.96$	$11.77 \pm 0.76$	$20.06 \pm 1.55$	62.17
C/N Ratio	7.71	15.45	46.12	10.12
Total N (%)	0.86	1.24	1.83	-
Total $P_2O_5$ (%)	$2.10 \pm 0.04$	-	-	-
Total $K_2O$ (%)	$1.26 \pm 0.01$	-	-	$1.72 \pm 0.10$

## Changes in Composting Parameters

### Temperature

Temperature plays a crucial role in the composting process, as it affects the microbial activity responsible for breaking down organic matter. During aerobic decomposition under optimal moisture conditions, microorganisms generate heat (Aggie Horticulture 2009; Food and Agriculture Organization 2021). The temperature profile of composting is typically divided into four phases: mesophilic (15 to 43 °C), thermophilic (43 to 72 °C), cooling down, and maturing—where the temperature approaches ambient levels (Xie *et al.* 2023).

As shown in Fig. 3, in this study, on day 24, the internal temperature of all reactors was approximately 1 to 4 °C higher than the ambient temperature. Reactors R6 and R7 recorded the highest temperatures between days 35 to 37 at  $40.00\pm 0.58$  °C and  $40.67\pm 0.58$  °C, respectively, which are in the mesophilic range. It is possible that microbial activator in both reactors attributable to biological metabolism resulting in the temperature shot up. The reason the temperature did not reach the thermophilic phase in any reactor may be due to the relatively small quantity of composting materials and low ambient temperatures at the time. This observation is consistent with previous findings (Castillo-González *et al.* 2019), indicating that when composting remains within the mesophilic range and does not enter the thermophilic phase, organic matter degradation is primarily driven by mesophilic microorganisms, which is typically associated with low-temperature or slow composting processes. The elevated temperatures in R6 and R7 are likely due to increased microbial activity stimulated by the microbial activator. Reactor R6 contained biogas sludge, shredded EFB, the microbial activator, and was aerated, while R7 included the same components plus earthworms and dried cow dung. As composting progressed, the temperature in all reactors gradually declined to ambient levels. Earthworms were added to R3, R5, and R7 during week 6, as the optimal temperature for their activity ranges from 25 to 37 °C (Barthod *et al.* 2018).



**Fig. 3.** Changes in temperature during the composting process (R1: 100%BS; R2: 100%BS +FA; R3:100%BS+EW+FA; R4: 50%BS+50%EFB; R5: 50%BS+50%EFB+FA; R6: 50%BS+50%EFB+EW+FA; R7: 50%BS+50%EFB+MA+FA; where BS is Biogas Sludge, FA is Force Air, EW is Earth Worm, MA is Microbial Activator)

By the end of the composting period (week 11), the temperature in all reactors was below ambient, with recorded temperatures of  $25.33\pm 0.58$  °C for R1,  $25.00\pm 1.00$  °C for R2,  $25.67\pm 0.58$  °C for R3,  $25.67\pm 0.58$  °C for R4,  $25.33\pm 0.58$  °C for R5,  $25.00\pm 0.58$  °C for R6, and  $25.00\pm 0.00$  °C for R7, as shown in Fig. 3. This was likely due to heat dissipation

during the cooler nighttime period, while temperature measurements were conducted in the late morning after the ambient temperature had risen.

### Moisture content

Moisture is a critical parameter in the composting process because it is essential for microbial activity. Microorganisms require moisture to transport nutrients and energy across cell membranes (Roman *et al.* 2015). The optimal moisture content (MC) for composting is between 45% to 60% (Ameen *et al.* 2016; Meena *et al.* 2021; Wang *et al.* 2022). If the MC drops below 40%, microbial activity halts, potentially leading to dormancy (Kawai *et al.* 2020). Conversely, if the MC exceeds 80%, the composting process may shift from aerobic to anaerobic conditions, as excess water fills the pores between compost materials, preventing oxygen from diffusing into the compost and possibly causing foul odors.

Experimental results showed that the initial MC in reactors R1 to R7 ranged from 31.05±3.82% to 53.48±4.13%. Reactors R1 to R3 had relatively low MCs (31.05±3.82%, 31.66±2.41%, and 31.05±2.87%, respectively), so water was added to increase the moisture level. During weeks 1 to 4, moisture levels were within the optimal range but decreased in week 5 due to evaporation as temperatures entered the thermophilic phase. In week 6, earthworms were added to reactors R3, R5, and R7. The optimal MC for earthworm survival was 45% to 60% (Nsiah-Gyambibi *et al.* 2021), so MC was increased accordingly. Results from the vermicomposting process showed moisture contents of 48.30±0.29%, 55.65±1.47%, and 51.50±1.63% in R3, R5, and R7, respectively. At the end of the composting process in week 11, the MC in all reactors ranged from 33.80±4.65% to 44.20±2.82% (as shown in Fig. 4), which did not meet the Department of Agriculture organic fertilizer standard (Department of Agriculture 2012) that requires MC not to exceed 30%. However, the final compost product can be further dried to meet the required standard.

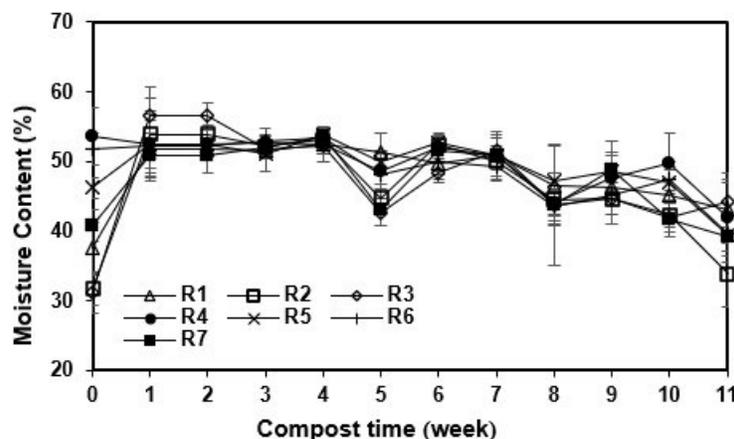
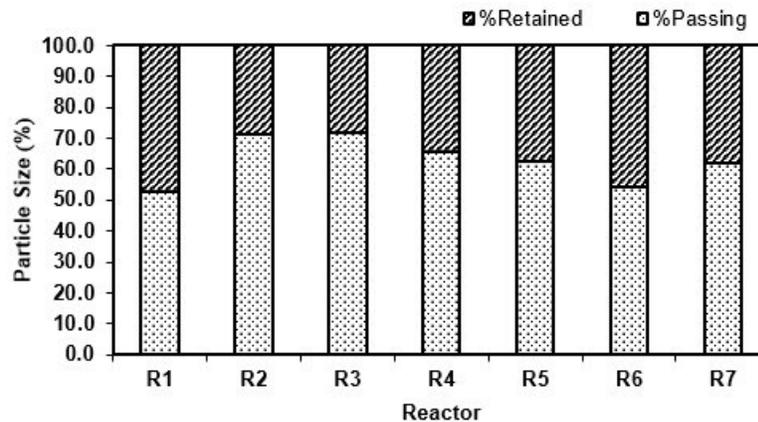


Fig. 4. Changes in moisture content during the composting process

### Particle size

The particle size of compost indicates the completeness of the decomposition process. According to the standards set by the Department of Agriculture of Thailand, fully decomposed compost should be able to pass through a 12.5 × 12.5 mm sieve entirely, using the dry screen method (Department of Agriculture 2008). Experimental results at week 11 showed that the proportion of compost passing through the sieve in reactors R1 to R7 was

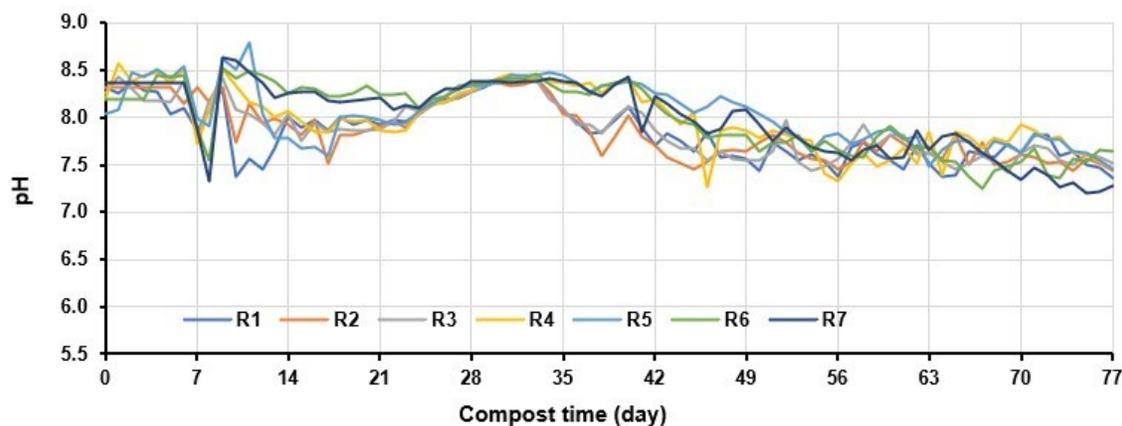
52.7%, 71.5%, 71.9%, 65.7%, 62.4%, 54.5%, and 61.8%, respectively. Reactor R3 had the highest proportion of compost passing through the sieve (71.9%), while R1 had the lowest (52.7%). This may be because R1 relied solely on natural aeration and did not use a mechanical aerator (Fig. 5).



**Fig. 5.** Percentage of compost passing through a 12.5 × 12.5 mm sieve (%)

### pH

Microorganisms can decompose organic materials biologically over a wide pH range (pH 3 to 11), but the optimal pH for microbial activity is between 5.5 and 8.0 (Bernal *et al.* 2009; Raza and Leahu 2020). Therefore, changes in pH during the composting process are important for the growth and degradation activity of microorganisms. Experimental results showed that the initial pH was slightly alkaline, ranging from  $8.03 \pm 0.03$  to  $8.36 \pm 0.06$ .



**Fig. 6.** Changes in pH during the composting process

The pH of compost material influences the decomposition rate, with alkaline pH being more favorable for composting than acidic pH. This is because, at low pH, microorganisms may be damaged, resulting in a lower decomposition rate. Starting from week 2, the pH gradually decreased to neutral and then slowly increased. In week 6, earthworms were added to reactor 3, 5, and 7, and at that time, the pH remained slightly alkaline. However, cow manure was added to adjust the conditions inside the reactors to make them suitable for the earthworms. The pH throughout the experiment ranged from 7.20 to 8.80. By week 11, the pH in reactors R1 to R7 was neutral, ranging from  $7.32 \pm 0.03$

to  $7.83 \pm 0.04$ , which meets the standard set by the Department of Agriculture (2012) that requires a pH between 5.5 and 8.5 (as shown in Fig. 6).

#### Electrical conductivity

Electrical conductivity (EC) is a measure of the total concentration of charged substances dissolved in the solution of organic fertilizer. Changes in EC depend on the amount of dissolved minerals in the suspension (Ghinea and Leahu 2020) and indicate the level of salinity. If the EC is high, it may indicate that the fertilizer has a high concentration or a high amount of salts, which can reduce or impair the ability of plant roots to absorb water and nutrients. This can lead to dehydration and wilting of the leaves. Applying compost with EC values greater than 4 mS/cm to soil may have adverse effects on plant growth (Smith 2009; Li *et al.* 2012). The experimental results showed that at the beginning of the composting process, the EC in all reactors were between  $2.59 \pm 0.21$  and  $3.27 \pm 0.21$  dS/m. In reactors R4, R5, R6, and R7, the conductivity gradually increased during the first two weeks and then decreased as the composting process neared completion. In contrast, reactor R1, R2, and R3 showed more variation in the conductivity values. At the end of the composting process, the EC in all 7 reactors ranged from  $2.26 \pm 0.04$  to  $2.99 \pm 0.05$  dS/m, which meets the Department of Agriculture's standard of not exceeding 10 dS/m (as shown in Fig. 7).

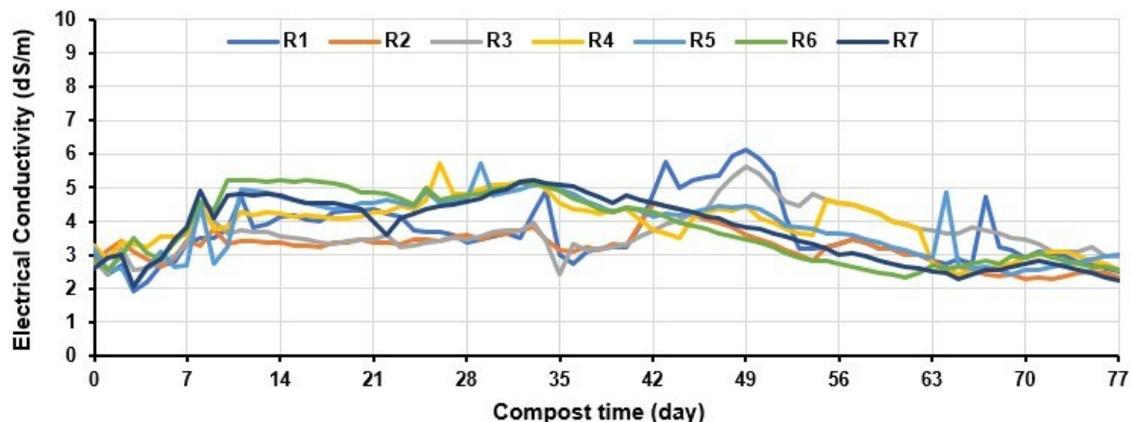


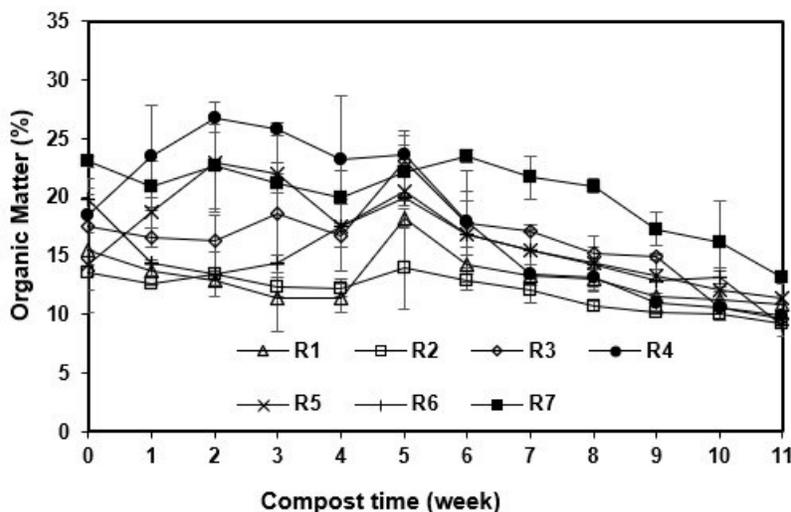
Fig. 7. Changes in electrical conductivity during the composting process

Although hydronium and hydroxyl ions possess high ionic mobility, their contribution to the overall electrical conductivity is negligible under the pH conditions observed in this study. At pH 8, the estimated contribution of  $\text{H}_3\text{O}^+$  and  $\text{OH}^-$  to EC is approximately  $2 \times 10^{-4} \text{ dS} \cdot \text{m}^{-1}$ , representing less than 0.01% of the measured conductivity ( $\sim 2.5 \text{ dS} \cdot \text{m}^{-1}$ ). This indicates that variations in EC are mainly controlled by the concentrations of dissolved inorganic ions rather than by pH-related proton dynamics. Prior studies (Agmon *et al.* 2016) have also reported that  $\text{H}^+$  and  $\text{OH}^-$  exhibit significantly higher mobilities than other ions in water; however, their impact on overall conductivity is limited by their low abundance in the typical pH range.

#### Organic matter

The amount of organic carbon or organic matter in each type of compost material varies in quantity and composition. This organic matter (OM) is decomposed and utilized as an energy source by microorganisms. Adequate oxygen levels help promote the growth of bacteria that decompose organic materials (Wang *et al.* 2025). The amount of organic

carbon (OC) is related to the quantity of OM, and the OM content indicates the extent of decomposition of the compost material. Therefore, the amount of OC should tend to decrease, and as OC decreases, OM content will also decrease.



**Fig. 8.** Changes in organic matter during the composting process

The resulting compost should contain OM not less than 20% by weight (Department of Agriculture 2012). Experimental results at the beginning of the study showed that the OM content ranged from  $13.54 \pm 3.42\%$  to  $23.05 \pm 0.52\%$ . After 7 weeks, the OM content tended to decrease, ranging from  $12.02 \pm 1.07\%$  to  $21.72 \pm 1.82\%$ . By the end of the composting process in week 11, the OM content ranged from  $9.17 \pm 0.97\%$  to  $13.2 \pm 0.55\%$ , with all reactors failing to meet the Department of Agriculture's standard (Department of Agriculture 2012) (as shown in Fig. 8).

#### *C/N ratio*

The C/N ratio is an important parameter used to assess the progress and maturity of the composting process. The C/N ratio of each compost material differs. If the C/N ratio is low, it can result in nitrogen loss in the form of ammonia gas, which may inhibit microbial activity and cause odors (Azim *et al.* 2018; Long *et al.* 2019). Conversely, if the initial C/N ratio is high, biological degradation occurs slowly and takes longer. The ideal C/N ratio is between 25 to 40, as microorganisms use carbon from the degradation of carbohydrates to convert into sugars, organic acids, and carbon dioxide gas as an energy source, and use nitrogen from protein degradation. In this study, the initial C/N ratio of the 50% biogas sludge + 50% EFB mixture was calculated to be 8.48 (R4-R7). Experimental results showed that the initial C/N ratio ranged from 7.68 to 18.30, which was low, leading to slow organic degradation. The C/N ratio was quite variable from the beginning until week 5, but by week 6, the C/N ratio showed a decreasing trend throughout the experiment. At the end of the composting process, the C/N ratio in all reactors met the organic fertilizer standard, which specifies that the C/N ratio must be less than 20 (Department of Agriculture 2012), as shown in Fig. 9.

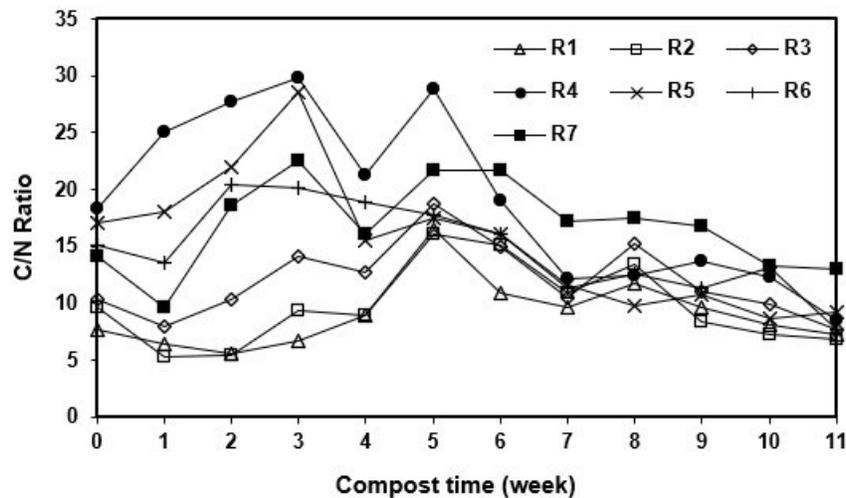


Fig. 9. Changes in the C/N ratio during the composting process

### Total nitrogen

Nitrogen is a major nutrient required by microorganisms for growth, as it is used in protein synthesis. The experimental results showed that the initial total nitrogen content in compost R1 to R7 were 0.86%, 1.22%, 1.01%, 1.70%, 1.98%, 1.40%, and 1.02%, respectively.

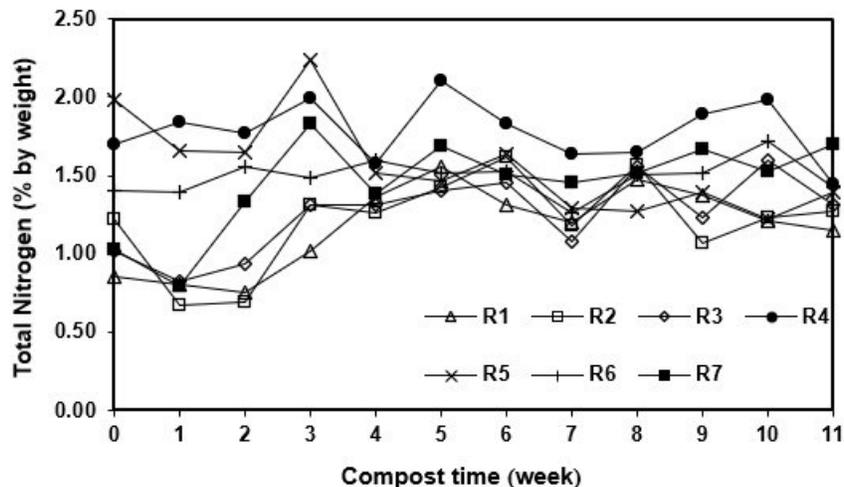


Fig. 10. Changes in total nitrogen during the composting process

These initial N values were measured per reactor. In the first 6 weeks, reactors R1, R2, and R3 showed an increasing trend, while reactors R4, R5, R6, and R7 showed rather variable nitrogen content. At the end of the composting process (week 11), the total nitrogen content in reactors R1 to R7 was 1.15%, 1.27%, 1.31%, 1.44%, 1.39%, 1.42%, and 1.70%, respectively. The reactor with the highest total nitrogen content was reactor R7 (1.70%), which contained Super LDD 1 along with earthworms, while the reactor with the lowest total nitrogen content was reactor R1 (1.15%), the control group, which contained only sludge from the biogas system and used natural oxygen. However, all compost reactors met the Department of Agriculture's standard, which requires a total nitrogen content of at least 1% by weight, as shown in Fig. 10.

### Total P<sub>2</sub>O<sub>5</sub>

Phosphorus is a nutrient used by microorganisms for growth in the compost pile. It was present in the form of diphosphorus pentoxide (total P<sub>2</sub>O<sub>5</sub>). Phosphorus is a macronutrient required by plants in relatively large amounts. Although the P content in plants is generally lower than that of nitrogen and potassium, its role is crucial, as it is a key element for plant growth and development (Abdullahi *et al.* 2020). Phosphorus affects plant growth in areas related to flowering, seed formation, root system development, and accelerates plant maturity. According to experimental results, the initial total P<sub>2</sub>O<sub>5</sub> content in reactors R1 to R3 (100% biogas sludge) was 2.10±0.04%, and at the end of the composting process, it was 1.85±0.01%, 1.68±0.02%, and 1.74±0.02%, respectively, showing a decrease in all reactors. In contrast, reactors R4 to R7 (50% biogas sludge + 50% shredded empty palm bunches) had an initial total P<sub>2</sub>O<sub>5</sub> content of 1.75±0.02%, and at the end of the composting process, it was 2.22±0.04%, 1.71±0.01%, 2.07±0.01%, and 2.00±0.01%, respectively, showing an increase in all reactors except reactor R5, which had a slight decrease. The reactor with the highest total P<sub>2</sub>O<sub>5</sub> was reactor R4, which had biogas sludge and shredded empty palm bunches (in a 1:1 ratio) with aeration. The reactor with the lowest total P<sub>2</sub>O<sub>5</sub> was reactor R2. At the end of the composting process, the total P<sub>2</sub>O<sub>5</sub> content in all reactors met the Department of Agriculture's standard, which specifies that the phosphorus content in the form of total P<sub>2</sub>O<sub>5</sub> should not be less than 0.5% by weight (Department of Agriculture 2012), as shown in Fig. 11.

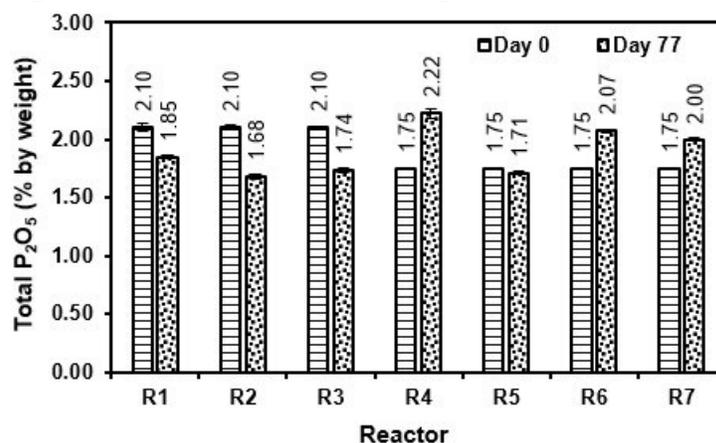


Fig. 11. Total phosphorus (Total P<sub>2</sub>O<sub>5</sub>) at the end of the composting process

### Total K<sub>2</sub>O

Potassium is an essential nutrient for plant growth, and the potassium that plants utilize is in the form of potassium ions (K<sup>+</sup>). Potassium enhances overall plant development as well as the production of carotene and chlorophyll (Razaq *et al.* 2017). Additionally, K contributes to plant vigor and vibrant coloration. It plays a key role in sugar synthesis within the plant and is vital for building resistance to diseases and tolerating environmental stresses such as drought and cold temperatures. A deficiency in K can result in scorched and browned tips on older leaves, which may eventually spread to the entire leaf. Weak stems may also indicate a lack of K. According to Kammoun *et al.* (2017), composts serve as a rich source of phosphorus, which is another important nutrient for plant growth. Potassium also plays a role in protein synthesis, improving crop quality, and reducing plant diseases. Its key functions include stimulating the activity of several enzymes involved in starch, sugar, and protein synthesis and regulating the opening and

closing of stomata. When plants are deficient in K, the edges of older leaves turn yellow, leaf margins curl, and the yield is smaller. According to experimental results, the initial total  $K_2O$  content in reactors R1 to R3 (100% biogas sludge) was  $1.26\pm 0.00\%$ , and at the end of the composting process, it was  $0.88\pm 0.01\%$ ,  $0.75\pm 0.01\%$ , and  $0.82\pm 0.01\%$ , respectively, showing a decrease in all reactors. In contrast, reactors R4 to R7 (50% biogas sludge + 50% shredded empty palm bunches) had an initial total  $K_2O$  content of  $1.05\pm 0.04\%$ , and at the end of the composting process, it was  $1.31\pm 0.04\%$ ,  $1.09\pm 0.04\%$ ,  $1.27\pm 0.04\%$ , and  $1.35\pm 0.04\%$ , respectively, showing an increase in all reactors. Reactor R7 had the highest total  $K_2O$ , which was attributed to the fact that it contained the accelerator and earthworms to aid in the decomposition process. Reactor R2 had the lowest total  $K_2O$ . At the end of the composting process, the total  $K_2O$  content in all reactors met the Department of Agriculture's standard, which specifies that the K-content in the form of total  $K_2O$  should not be less than 0.5% by weight, as shown in Fig. 12.

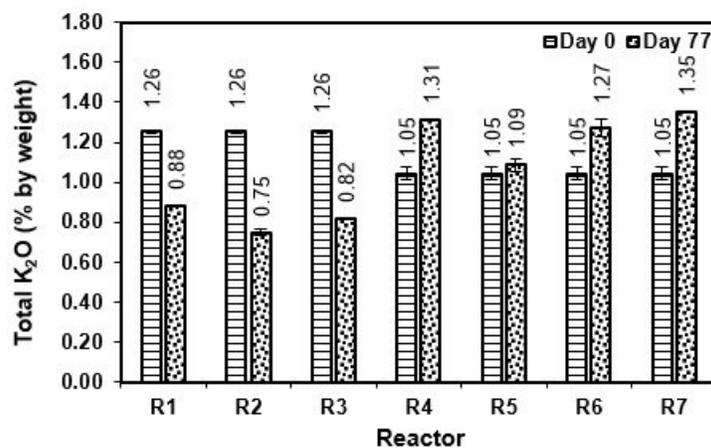
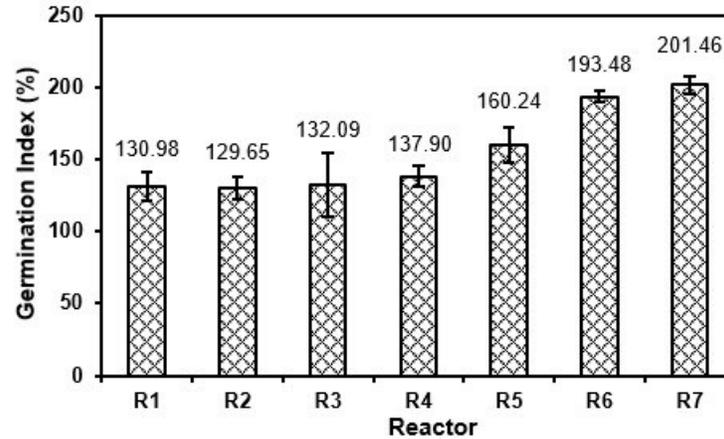


Fig. 12. Total potassium (Total  $K_2O$ ) at the end of the composting process

### Germination index

The complete biodegradation of organic fertilizers can be measured using various methods, such as seed germination tests, cation exchange capacity, C/N ratio analysis, and germination index testing. This study used the germination index (GI) method, which can assess phytotoxic substances that remain in organic fertilizers produced during the composting process or in fertilizers that have not yet fully decomposed (Ko *et al.* 2008). In this experiment, the GI was tested using East-West Seed brand Chinese cabbage seeds, which had a germination rate of 100%. Distilled water was used as a control, and compost extract from all seven compost reactors was used in the tests. The GI values of Chinese cabbage seeds from reactors R1 to R7 were  $130.98\pm 9.56\%$ ,  $129.65\pm 7.64\%$ ,  $132.09\pm 21.99\%$ ,  $137.90\pm 7.18\%$ ,  $160.24\pm 12.16\%$ ,  $193.48\pm 3.99\%$ , and  $201.46\pm 6.28\%$ , respectively. All seven composts met the Department of Agriculture's standard for organic fertilizers, which requires a germination index of at least 80%, as stated by (Luo *et al.* 2018), as shown in Fig. 13. This result is consistent with the research of Islam *et al.* (2021), who studied the changes in the chemical properties of banana waste, mushroom cultivation residues, and chicken manure through the composting process. The best ratio of banana waste : mushroom cultivation residues : chicken manure was 1:2:1, which had a GI of 129%. The GI values of all reactors were greater than 80%, indicating mature and phytotoxic-free compost (Pampuro *et al.* 2017; Mishra and Yadav 2022; ). GI also serves as a sensitive biological indicator for assessing compost safety and its suitability for agricultural purposes (Oued Lha *et al.* 2024). Oktawan *et al.* (2018) reported that compost

phytotoxicity was effectively eliminated when GI increased from 104.03 on day 21 of composting to 173.35 at a later stage. Furthermore, the loss of phytotoxicity is widely recognized as an important indicator of compost maturity. Therefore, the products from reactors R6 and R7 can be considered more completely matured composts compared to the other treatments.



**Fig. 13.** Germination Index (%) at the end of the composting process

#### *Physical changes of compost*

The physical characteristics of compost serve as indicators of the completion of the decomposition process. The physical properties of the compost materials in each reactor were studied over a period of 11 weeks, including color, smell, texture of the compost material, presence of organisms in the pile, and the volume of compost from the start to the end of the process. It was found that in the first week of composting, the materials in all the reactors had a solid texture and color, as decomposition had not yet occurred.

By week 5, the compost in reactors R4, R5, R6, and R7 had become crumbly, while compost in reactors R1, R2, and R3 remained hard, and the moisture content had decreased in all reactors. Therefore, in week 6, moisture and cow manure were added to reactors R3, R5, and R7 to adjust the conditions for earthworms.

At the end of the composting process in week 11, it was observed that the compost in reactors R1 and R2 was black and had decreased in size. In reactor R3, the compost was black and crumbly. In reactors R4, R5, and R6, the compost was black, crumbly, smaller, and contained some fibers. In reactor R7, the compost was loose, black, and contained a small amount of fibers. All seven composts had an earthy smell (Figs. 14 to 20).



**Fig. 14.** Reactor R1 Biogas system sludge (aeration by natural air) (a) Day 0; (b) week 5; and (c) week 1



**Fig. 15.** Reactor R2 Biogas system sludge + forced aeration (a) Day 0; (b) week 5; and (c) week 11



**Fig. 16.** Reactor R3 Biogas system sludge + earthworms + forced aeration (a) Day 0; (b) week 5; and (c) week 11



**Fig. 17.** Reactor R4 Biogas system sludge + shredded empty fruit bunches (EFB) + forced aeration (a) Day 0; (b) week 5; and (c) week 11x



**Fig. 18.** Reactor R5 Biogas system sludge + shredded empty fruit bunches (EFB) + earthworms + forced aeration (a) Day 0; (b) week 5; and (c) week 11



**Fig. 19.** Reactor R6 Biogas system sludge + shredded EFB + Super LDD1 microbial activator + forced aeration (a) Day 0; (b) week 5; and (c) week 11



**Fig. 20.** Reactor R7 – Biogas system sludge + shredded EFB + Super LDD1 microbial activator + earthworms + forced aeration (a) Day 0; (b) week 5; and (c) week 11

### Comparison of the Products with Organic Fertilizer Standards

In the experiment, the composts from all seven reactors in week 11 were compared with the organic fertilizer standards. Reactors R3, R5, and R7 contained vermicompost, for which there is currently no established standard. Therefore, in this experiment, the final products from the trial were compared with the standards set by the Department of Agriculture (2012), as shown in Table 5.

**Table 5.** Comparison of the Products with the Organic Fertilizer Standards (Department of Agriculture 2012)

Parameters	Standards	Reactors						
		R1	R2	R3	R4	R5	R6	R7
Moisture Content (%)	Not more than 30%	43.06 ×	33.80 ×	44.20 ×	41.89 ×	39.31 ×	39.48 ×	39.17 ×
Stone and Gravel Content (>5 mm)	>5 mm, ≤ 2% by weight	✓	✓	✓	✓	✓	✓	✓
Plastic, Glass, Sharp/Metallic Objects	None allowed	✓	✓	✓	✓	✓	✓	✓
Organic Matter (%)	≥ 20%	10.85 ×	9.17 ×	9.58 ×	9.92 ×	11.45 ×	9.10 ×	13.20 ×

Parameters	Standards	Reactors						
		R1	R2	R3	R4	R5	R6	R7
pH	5.5 - 8.5	7.35 ✓	7.43 ✓	7.52 ✓	7.45 ✓	7.45 ✓	7.65 ✓	7.28 ✓
C/N Ratio	< 20	7.24 ✓	6.76 ✓	7.69 ✓	8.51 ✓	9.23 ✓	7.63 ✓	13.02 ✓
EC (dS/m)	≤ 10	2.53 ✓	2.34 ✓	2.95 ✓	2.58 ✓	2.99 ✓	2.55 ✓	2.26 ✓
Total N (%)	≥ 1.0%	1.15 ✓	1.27 ✓	1.31 ✓	1.44 ✓	1.39 ✓	1.42 ✓	1.70 ✓
Total P <sub>2</sub> O <sub>5</sub> (%)	≥ 0.5%	1.85 ✓	1.68 ✓	1.74 ✓	2.22 ✓	1.71 ✓	2.07 ✓	2.00 ✓
Total K <sub>2</sub> O (%)	≥ 0.5%	0.88 ✓	0.75 ✓	0.82 ✓	1.31 ✓	1.09 ✓	1.27 ✓	1.35 ✓
Particle Size	≤ 12.5 x 12.5 mm	52.7 ✗	71.5 ✗	71.9 ✗	65.7 ✗	62.4 ✗	54.5 ✗	61.8 ✗
Complete Decomposition (Germination Index)	> 80%	130.98 ✓	129.65 ✓	132.09 ✓	137.90 ✓	160.48 ✓	193.40 ✓	201.46 ✓

**Note:** ✓ = Meets the standard  
✗ = Does not meet the standard

### Statistical analysis

One-way ANOVA revealed statistically significant differences among composting reactors for organic matter (OM), phosphorus (P<sub>2</sub>O<sub>5</sub>), potassium (K<sub>2</sub>O), and germination index (GI) ( $p < 0.05$ ), as shown in Table 6. In contrast, no significant difference was observed for nitrogen (N) ( $p = 0.310$ ).

Pairwise comparisons between composting reactors were performed using two-tailed post hoc student's t-tests with Bonferroni correction in Microsoft Excel (adjusted significance level:  $\alpha_{\text{adjust}} = 0.00238$ ). As shown in Table 7, most reactor pairs exhibited statistically significant differences in nutrient-related parameters, particularly total phosphorus (P<sub>2</sub>O<sub>5</sub>), total potassium (K<sub>2</sub>O), and total nutrients (N+ P<sub>2</sub>O<sub>5</sub>+ K<sub>2</sub>O). In contrast, organic matter (OM) and germination index (GI) showed relatively fewer significant differences among reactors, indicating more similar performance for these parameters across the systems.

**Table 6.** Anova of Physico-chemical and Biological Parameters

Parameters	ANOVA	Sum of squares	df	Mean square	F-value	p-value
OM	Between groups	39.745	6	6.624	10.144	0.000
	Within groups	9.142	14	0.653		
	Total	48.887	20			
P <sub>2</sub> O <sub>5</sub>	Between groups	0.515	6	0.086	171.681	0.000
	Within groups	0.003	7	0.001		
	Total	0.519	13			

K <sub>2</sub> O	Between groups	0.754	6	0.126	270.764	0.000
	Within groups	0.003	7	0.000		
	Total	0.758	13			
N	Between groups	0.664	6	0.111	1.475	0.310
	Within groups	0.525	7	0.075		
	Total	1.190	13			
GI	Between groups	21997.61	6	3666.269	28.901	0.000
	Within groups	2663.96	21	126.855		
	Total	24661.57	27			

No significant differences were observed among the biogas-sludge-only reactors (R1, R2, and R3) in terms of OM, total P<sub>2</sub>O<sub>5</sub>, total K<sub>2</sub>O, or total nutrients (N + P<sub>2</sub>O<sub>5</sub> + K<sub>2</sub>O). The average total nutrient content of reactors containing EFB (R4–R7) was significantly higher than that of reactors using biogas sludge alone (R1 to R3). The highest OM content was observed in R7; however, no significant differences were found between R7 and R1, R2, or R5. This indicates that biogas-sludge-only systems without earthworms (R1 and R2) retained relatively high levels of OM. Furthermore, vermicomposting of biogas sludge with EFB (R5 and R7) significantly increased OM compared with the non-vermicomposting reactors (R4 and R6). This finding is consistent with previous reports (Elissen *et al.* 2023), indicating that vermicomposting enhances organic matter transformation and increases the content of stable humic and fulvic acids, thereby contributing to higher organic matter levels in vermicompost.

Pairwise comparisons revealed no significant differences in total P<sub>2</sub>O<sub>5</sub> among R1, R2, and R3. Furthermore, R1 and R3 did not differ significantly from R4 to R7, whereas R2 differed significantly from R6. Comparisons between R4 and R5, R4 and R6, and R4 and R7 were not significant, while significant differences were observed between R5 and R6 and between R5 and R7. The observed differences in total P<sub>2</sub>O<sub>5</sub> were mainly associated with phosphorus mobilization rather than actual phosphorus input. Since biogas sludge was the primary phosphorus source and EFB contains low phosphorus, most reactors exhibited comparable total P<sub>2</sub>O<sub>5</sub> levels. However, the significant difference between R2 and R6 suggests that microbial activator enhanced phosphorus solubilization, thereby increasing the measurable P fraction. This finding is consistent with previous studies (Bohórquez-Sandoval *et al.*, 2025) reporting that microbial communities harboring phosphorus-cycling genes (*e.g.*, *gcd*, *phoA*, *phoD*) play a crucial role in phosphorus mineralization and solubilization, leading to higher phosphorus availability without increasing total phosphorus content. In contrast, earthworm addition alone (R5) had a limited effect on phosphorus mobilization compared with microbial treatment.

**Table 7.** p-Value (two tail) between Reactor Pairs

Pair Comparison		Organic Matter	Total P <sub>2</sub> O <sub>5</sub>	Total K <sub>2</sub> O	Total Nutrient (N+ P <sub>2</sub> O <sub>5</sub> + K <sub>2</sub> O)	GI
Reactors	Reactors					
R1	R2	0.21444	0.01044	0.00791	0.01045	0.83513
	R3	0.28910	0.02370	0.00791	0.49291	0.63539
	R4	0.40504	0.00723	0.00816	*0.00084	0.29133
	R5	0.58211	0.01005	*0.00013	0.00254	0.00916
	R6	0.15498	0.00410	0.01442	*0.00024	*0.00002
	R7	0.08747	0.00877	0.00588	*0.00015	*0.00002
R2	R3	0.55562	0.10557	0.01980	0.01713	0.55284

	R4	0.24764	0.00377	*0.00032	*0.00070	0.16683
	R5	0.01623	0.19171	0.00640	*0.00157	0.00533
	R6	0.91185	*0.00208	0.00368	*0.00028	*0.00001
	R7	0.00327	0.00306	*0.00028	*0.00018	*0.00001
R3	R4	0.32708	0.00474	*0.00005	*0.00092	0.93846
	R5	0.00489	0.29986	0.00878	0.00371	0.11341
	R6	0.21234	0.00288	0.00442	*0.00038	*0.00231
	R7	*0.00121	0.00459	*0.00011	*0.00023	*0.00133
R4	R5	*0.00028	0.00382	0.01212	*0.00152	0.01948
	R6	*0.00097	0.04168	0.31401	0.02951	*0.00001
	R7	*0.00050	0.02004	0.01686	0.12713	*0.00001
R5	R6	*0.00010	*0.00154	0.04179	*0.00050	*0.00203
	R7	0.00669	*0.00237	0.00878	*0.00025	*0.00095
R6	R7	*0.00024	0.03848	0.11655	0.00295	0.07576

\*indicates statistically significant differences between reactor pairs at  $p < 0.00238$  (Bonferroni correction)

Pairwise comparisons indicated no significant differences in total  $K_2O$  among R1, R2, and R3. Similarly, no significant differences were detected among R4 to R7. In contrast, significant differences were observed between R1 and R5, R2 and R4, R2 and R7, R3 and R4, and R3 and R7. The variation in total  $K_2O$  was mainly governed by substrate composition rather than biological treatments. Since biogas sludge contains relatively low potassium, reactors R1 to R3 exhibited similar  $K_2O$  levels. In contrast, all reactors containing EFB (R4 to R7) showed comparable and significantly higher  $K_2O$  contents due to the inherently high potassium concentration in plant-based materials. The effects of earthworms or microbial activator on potassium were secondary and were masked by the dominant contribution of EFB. Overall, total  $K_2O$  was primarily controlled by the presence of EFB, indicating that potassium availability in this system was substrate-driven rather than biologically regulated.

Although R7 showed the highest total nutrient content, the lack of significant difference compared with R4 and R6 suggests that substrate composition (EFB) was the dominant factor controlling nutrient levels. The limited effect of earthworm addition (R5) indicates that vermicomposting primarily enhances organic matter degradation and stabilization rather than increasing total nutrient mass. In contrast, microbial activator played a more critical role in nutrient mobilization, highlighting that vermicomposting should be integrated with microbial treatment to achieve optimal nutrient performance. Vermicomposting alone improves compost quality, but not nutrient density; nutrient enhancement requires microbial-driven nutrient mobilization.

The significantly higher GI values of 193 and 201 observed in R6 and R7 indicate a higher degree of compost maturity and non-phytotoxicity, mainly attributable to microbial activator. The lack of a significant difference between R6 and R7 further indicates that earthworm addition did not noticeably influence GI, suggesting that microbial activity was the dominant factor governing phytotoxicity reduction. In contrast, reactors R1 to R5 showed similarly lower GI values (although  $>80\%$ ), which may reflect suboptimal nutrient availability or the persistence of inhibitory compounds. This is consistent with previous findings that adequate levels of  $NH_4^+$  can enhance GI (Pampuro *et al.* 2017), whereas excessive concentrations may exert phytotoxic effects.

## CONCLUSIONS

This research involved composting using sludge from the biogas system of a crude palm oil extraction plant combined with shredded empty fruit bunches (EFB). The findings can be summarized as follows:

1. The properties of the sludge from the biogas system were as follows: pH  $8.30 \pm 0.03$ , electrical conductivity  $2.85 \pm 0.15$  dS/m, moisture content  $34.12 \pm 5.53\%$ , organic matter  $15.47 \pm 3.38\%$ , organic carbon  $8.97 \pm 1.96\%$ , carbon to nitrogen ratio 7.71, total nitrogen 0.86%, total phosphorus (as total  $P_2O_5$ )  $2.10 \pm 0.04\%$ , and total potassium (as total  $K_2O$ )  $1.26 \pm 0.01\%$ . These properties indicate that the sludge was suitable for use as a composting material.
2. Most parameters analyzed in all composting reactors met the organic fertilizer standards set by the Department of Agriculture (Thailand), except for moisture content and organic matter.
3. Composting reactors R3 (100% Biogas Sludge+Earthworm+ Forced air), R5 (50% Biogas Sludge + 50% EFB+ Earthworm+ Forced air), and R7 (50% Biogas Sludge + 50% EFB+ Earthworm+ Microbial activator + Forced air) had smaller and more friable composted material at the end of the process, due to the presence of earthworms which facilitated decomposition.
4. Composting reactor R7, which used both earthworms and the microbial activator, yielded the highest total nutrient content, with a combined value of 5.05% (Total N : Total  $P_2O_5$  : Total  $K_2O$  = 1.70% : 2.00% : 1.35%), the highest germination index ( $201.46 \pm 6.28\%$ ), and a friable texture with a dark color and earthy smell.
5. The compost products from all reactors were suitable to be used to improve soil quality.

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## REFERENCES CITED

- Abdullahi, A. B., Taha, M. R., Buba, Y. M., and Sabran, M. R. (2020). "Analysis of C-organic and total Phospor ( $P_2O_5$ ) contents of soil around egg-laying chicken farm," *IOP Conference Series: Earth and Environmental Science* 492(1), article 012090. <https://doi.org/10.1088/1755-1315/492/1/012090>
- Aggie Horticulture (2009). "The decomposition process," Chapter 1, (<https://aggiehorticulture.tamu.edu/earthkind/landscape/dont-bag-it/chapter-1-the-decomposition-process/>), accessed on 2nd September 2025.
- Agmon, N., Bakker, H. J., Campen, R. K., Henchman, R. H., Pohl, P., Roke, S., Thämer, M., and Hassanali, A. (2016). "Protons and hydroxide ions in aqueous systems," *Chemical Reviews* 116(13), 7642-7672. <https://doi.org/10.1021/acs.chemrev.5b00736>

- Ameen, A., Ahmad, J., and Raza, S. (2016). "Effect of pH and moisture content on composting of municipal solid waste," *International Journal of Scientific and Research Publications* 6(2), 35-37.
- Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S., and Alami, I.T. (2018). "Composting parameters and compost quality: A literature review," *Organic Agriculture* 8(2), 141-158. <https://doi.org/10.1007/s13165-017-0180-z>
- Barthod, J., Rumpel, C., and Dignac, M. F. (2018). "Composting with additives to improve organic amendments. A review," *Agronomy Sustainable Development* 38, article 17. <https://doi.org/10.1007/s13593-018-0491-9>
- Bernal, M. P., Alburquerque, J. A., and Moral, R. (2009). "Composting of animal manures and chemical criteria for compost maturity assessment. A review," *Bioresource Technology* 100(22), 5444-5453. <https://doi.org/10.1016/j.biortech.2008.11.027>
- Białobrzewski, I., Mikš-Krajnik, M., Dach, J., Markowski, M., Czekala, W., and Głuchowska, K. (2015). "Model of the sewage sludge-straw composting process integrating different heat generation capacities of mesophilic and thermophilic microorganisms," *Waste Management* 43, 72-83. <https://doi.org/10.1016/j.wasman.2015.05.036>
- Bohórquez-Sandoval, L. J., Hernandez-Lara, A., Gómez-Morte, J. A., Cuartero, J., García-Molano, J. F., Pascual, J. A., and Ros, M. (2025). "The potential bioavailability of phosphorus and the microbial community involved in agro-industrial composts as organic amendments or growing media," *Journal of Environmental Management* 386, article 125762. <https://doi.org/10.1016/j.jenvman.2025.125762>
- Castillo-González, E., Giral-di-Díaz, M. R., De Medina-Salas, L., and Sánchez-Castillo, M. P. (2019). "Pre-composting and vermicomposting of pineapple (*Ananas comosus*) and vegetable waste," *Applied Sciences* 9(17), article 3564. <https://doi.org/10.3390/app9173564>
- Department of Agriculture (2008). "Handbook of organic fertilizer analysis methods (Thai)," (<http://lib.doa.go.th/multim/e-book/EB00061.pdf>), Accessed on 2<sup>nd</sup> September 2025.
- Department of Agriculture (2012). "Announcement of the Department of Agriculture regarding the application for registration, issuance of registration certificates, amendment of registration details, and amendment of organic fertilizer registration entries B.E. 2555," (<https://www.doa.go.th/ard/wp-content/uploads/2019/11/FEDOA5.pdf>), accessed on 2<sup>nd</sup> September 2025.
- Elissen, H. J. H., Van der Weide, R., and Gollenbeek, L. (2023). "Effects of vermicompost on plant and soil characteristics – A literature overview," *Wageningen Research*, Report WPR- 995. <https://doi.org/10.18174/587210>
- Food and Agriculture Organization (2021). "Composting process and techniques," (<http://www.fao.org/3/y5104e/y5104e05.htm>), accessed on 7<sup>th</sup> September 2025.
- Ghinea, C., and Leahu, A. (2020). "Monitoring of fruit and vegetable waste composting process: Relationship between microorganisms and physico-chemical parameters," *Processes* 8(3), 1-15. <https://doi.org/10.3390/pr8030302>
- He, Y., Inamori, Y., Mizuochi, M., Kong, H., Iwami, N., and Sun, T. (2000). "Measurements of N<sub>2</sub>O and CH<sub>4</sub> from the aerated composting of food waste," *Science of the Total Environment* 254(1), 65-74. [https://doi.org/10.1016/S0048-9697\(00\)00439-3](https://doi.org/10.1016/S0048-9697(00)00439-3)

- Islam, M.S., Kasim, S., Alam, K. Md., Amin, A. M., Hun, T. G., and Haque, M. A. (2021). "Changes in chemical properties of banana pseudostem, mushroom media waste, and chicken manure through the co-composting process," *Sustainability* 13(15), article 8458. <https://doi.org/10.3390/su13158458>
- Jaipakdee, P., Prhomraksa, A., Taprit, S., Intaravicha, N., Srithongouthai, S., Kanokkantapong, V., and Supakata, N. (2025). "Characteristics of soil amendment produced from composting food waste and bioplastic bags," *Results in Engineering* 27, article 106396. <https://doi.org/10.1016/j.rineng.2025.106396>
- Kammoun, M., Ghorbel, I., Charfeddine, S., Kamoun, L., Gargouri-Bouzid, R., and Nouri-Ellouz, O. (2017). "The positive effect of phosphogypsum-supplemented composts on potato plant growth in the field and tuber yield," *Journal of Environment Management* 200, 475-483. <https://doi.org/10.1016/j.jenvman.2017.06.016>
- Kawai, K., Liu, C., and Gamaralalage, P. J. D. (2020). "CCET guideline series on intermediate municipal solid waste treatment technologies: composting," (<https://www.iges.or.jp/en/pub/ccet-guideline-series-intermediate-municipal-solid-waste-treatment-technologies-composting/en>), Accessed on 9th June 2025.
- Ko, H. J., Kim, K. Y., Kim, H. T., Kim, C. N., and Umeda, M. (2008). "Evaluation of maturity parameters and heavy metal contents in composts made from animal manure," *Waste Management* 28(5), 813-820. <https://doi.org/10.1016/j.wasman.2007.05.010>
- Kumar, M., Ou, Y. L., and Lin, J. G. (2010). "Co-composting of green waste and food waste at low C/N ratio," *Waste Management* 30(4), 602-609. <https://doi.org/10.1016/j.wasman.2009.11.023>
- Li, R., Wang, J. J., Zhang, Z., Shen, F., Zhang, G., Qin, R., Li, X., and Xiao, R. (2012). "Nutrient transformations during composting of pig manure with bentonite," *Bioresource Technology* 121, 362-368. <https://doi.org/10.1016/j.biortech.2012.06.065>
- Liew, C. S., Yunus, N. M., Chidi, B. S., Lam, M. K., Goh, P. S., Mohamad, M., Sin, J. C., Lam, S. M., Lim, J. W., and Lam, S. S. (2022). "A review on recent disposal of hazardous sewage sludge via anaerobic digestion and novel composting," *Journal of Hazardous Materials* 423, article 126995. <https://doi.org/10.1016/j.jhazmat.2021.126995>
- Long, L., Xu, F., Ge, X., and Li, Y. (2019). "Biological treatment of organic materials for energy and nutrients production: Anaerobic digestion and composting," *Advances in Bioenergy* 4, 121-181. <https://doi.org/10.1016/bs.aibe.2019.04.002>
- Luo, Y., Liang, J., Zeng, G.M., Chen, M., Mo, D., Li, G.X., and Zhang, D. F. (2018). "Seed germination test for toxicity evaluation of compost: Its roles, problems and prospects," *Waste Management* 71, 109-114. <https://doi.org/10.1016/j.wasman.2017.09.023>
- Meena, A. L., Karwal, M., Dulta, D., and Mishra, R. P. (2021). "Composting: Phases and factors responsible for efficient and improved composting," *Agriculture and Food: E-Newsletter* 3(1), 85-90. <https://doi.org/10.13140/RG.2.2.13546.95689>
- Mishra, S. K., and Yadav, K. D. (2022). "Assessment of the effect of particle size and selected physico-chemical and biological parameters on the efficiency and quality of composting of garden waste," *Journal of Environmental Chemical Engineering*, 10(3), article 107925. <https://doi.org/10.1016/j.jece.2022.107925>
- Mustamu, N. E., and Triyanto, Y. (2020). "Nature of chemical and biological sludge biogas liquid waste oil palm," *International Journal of Innovative Science and Research Technology* 5(2), 955-957.

- Nsiah-Gyambibi, R., Essandoh, H. M. K., Asiedu, N.Y., and Fei-Baffoe, B. (2021). "Valorization of fecal sludge stabilization via vermicomposting in microcosm enriched substrates using organic soils for vermicompost production," *Heliyon* 7(3), article e06422. <https://doi.org/10.1016/j.heliyon.2021.e06422>
- Nutongkaew, T., Duangsuwan, W., Prasertsan, S., and Prasertsan, P. (2011). "Production of compost from palm oil mill biogas sludge mixed with palm oil mill wastes and biogas effluent," in: *TIChE International Conference*, (Hatyai, Songkhla, Thailand, pp. 1-5.
- Oktiawan, W., Zaman, B., and Purwono. (2018). "Use of a germination bioassay to test compost maturity in Tekelan Village," *E3S Web of Conferences* 31, article 05012. <https://doi.org/10.1051/e3sconf/20183105012>
- Onursal, E., and Ekinici, K. (2016). "A kinetic study on how C/N ratio affects energy consumption of composting of rose oil-processing wastes with caged layer manure and straw," *Environmental Progress and Sustainable Energy* 36(1), 129-137. <https://doi.org/10.1002/ep>
- Oueld Lhaj, M., Moussadek, R., Mouhir, L., Mdarhri Alaoui, M., Sanad, H., Iben Halima, O., and Zouahri, A. (2024). "Assessing the evolution of stability and maturity in co-composting sheep manure with green waste using physico-chemical and biological properties and statistical analyses: A case study of Botanique Garden in Rabat, Morocco," *Agronomy* 14(7), article 1573. <https://doi.org/10.3390/agronomy14071573>
- Pampuro, N., Bisaglia, C., Romano, E., Brambilla, M., Foppa Pedretti, E., and Cavallo, E. (2017). "Phytotoxicity and chemical characterization of compost derived from pig slurry solid fraction for organic pellet production," *Agriculture* 7(11), article 94. <https://doi.org/10.3390/agriculture7110094>
- Raza, S., and Ahmad, J. (2016). "Composting process: A review," *International Journal of Biological Research* 4(2), 102-104. <https://doi.org/10.14419/ijbr.v4i2.6354>
- Razaq, M., Zhang, P., and Shen, H. L. (2017). "Influence of nitrogen and phosphorous on the growth and root morphology of Acer mono," *PLoS One* 12, article e0171321. <https://doi.org/10.1371/journal.pone.0171321>
- Riddick, S. N., Mauzerall, D. L., Celia, M., Harris, N. R., Pitt, J., Staunton-Sykes, J., Forster, G. L., Kang, M., Lowry, D., Nisbet, E. G., and Manning, A. J. (2019). "Methane emissions from oil and gas platforms in the North Sea," *Atmospheric Chemistry and Physics* 19(15), 9787-9796.
- Roman, P., Martinez, M. M., and Pantoja, A. (2015). *Farmer's Compost Handbook: Experiences in Latin America*, (<http://www.fao.org/3/a-i3388e.pdf>), Accessed on 6th February 2025
- Smith, S. R. (2009). "A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge," *Environment International* 35(1), 142-156. <https://doi.org/10.1016/j.envint.2008.06.009>
- Soobhany, N., Mohee, R., and Gang, V. K. (2015). "Recovery of nutrient from Municipal Solid Waste by composting and vermicomposting using earthworm *Eudrilus eugeniae*," *Journal of Environmental Chemical Engineering* 3(4), 2931-2942. <https://doi.org/10.1016/j.jece.2015.10.025>
- Wang, A., Xue, J., Pang, B., Wang, H., Xu, Z., Chang, R., and Li, Y. (2025). "Bioaugmentation strategy for mitigating pollutant gas emissions in food waste composting using fermented mixtures," *Environmental Technology and Innovation* 37, article 103919. <https://doi.org/10.1016/j.eti.2024.103919>

- Wang, S. P., Wang, L., Sun, Z. Y., Wang, S. T., Yuan, H. W., An, M. Z., Tang, Y. Q., Shen, C. H., and Kida, K. (2022). "Effect of distillery sewage sludge addition on performance and bacterial community dynamics during distilled grain waste composting," *Bioresource Technology* 345, article 126486.  
<https://doi.org/10.1016/j.biortech.2021.126486>
- Xie, S., Tran, H. T., Pu, M., and Zhang, T. (2023). "Transformation characteristics of organic matter and phosphorus in composting processes of agricultural organic waste: Research trends," *Materials Science for Energy Technologies* 6, 331-342.  
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