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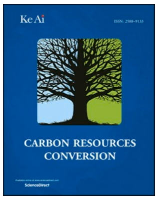

Comparative study on passive aerated in-vessel composting of food wastes with the addition of *Sabah ragi*

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ABSTRACT

The aims of this study are to determine the effect of Sabah ragi on food waste and dry leaves composting as well as to compare the composting performance from a previous study that had no addition of Sabah ragi. The composting process was conducted using an in-vessel passive aerated bioreactor with turning every 3 days for 40 days. Based on the physiochemical analysis, the stability and maturity of the compost were evaluated. Parameters such as temperature, total organic carbon, moisture content, pH, conductivity, and C/N were monitored. During the composting process, the highest temperature of 54.2 °C and the highest heat generation rate per initial mass of compost dry matter of 4098 kJ kg^{-1} day^{-1} was achieved on day 7. Furthermore, when compared to previous studies, this study achieved a faster thermophilic phase ($\geq$45 °C), a longer thermophilic period (4 days), and a higher cumulative temperature. Elementary kinetic analysis was performed based on the TOC profile and evaluated using coefficient correlation (R^2). In this study, application of the second-order model resulted in good responses. Low pathogen levels and higher nitrogen content were detected in the final compost, while some of the nutrients were not in the recommended range. An estimated ragi cost of RM 1.22 was required for every 1 kg of compost with a selling price of RM 6.00/kg of compost.

1. Introduction

Developing countries are currently experiencing increasing urbanization and industrialization. As a result, sustainable municipal solid waste (MSW) management is gaining traction as a means of addressing the waste problem. Every day, over 1.13 million tons of food waste are thrown away globally [1]. According to SWCorp [2], Malaysia generated 38,200 tons of waste per day in 2020, with 44.4 % of it being food waste, and a recycling rate of less than 30 %. Furthermore, food waste from houses, restaurants, and processing facilities is free of heavy metals and other hazardous chemicals, making it suitable for conversion as agricultural compost [3]. As a result, composting is regarded as a viable option to deal with food waste..

Due to the low level of selective collection and recycling practiced in Asian countries [4], landfills are preferred for the disposal of MSW. Furthermore, food waste accumulation in landfills drives negative impacts on the environment, economy, and community, such as greenhouse gas (GHG) emissions and groundwater contamination [5]. As a result, biological processes such as composting are recommended as a feasible alternative for waste management and recycling of waste-derived products. Composting technologies are divided into three major phases: mixture preparation, bio-oxidative phase, and the maturation phase [6]. The satisfaction and effectiveness of the composting process are influenced by several factors, including the properties of the starting materials, operational conditions, and maturation time [1,7]. In addition, food waste has certain limitations as a biowaste, such as a low C/N ratio, high moisture content, poor porosity, and nutritional deficiencies such as total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP), all of which have an influence on compost quality [8]. As a result, operational measures for composting should be addressed in order to speed up the process.

Ragi is widely used in Sabah as a fermentation starter for food or beverage fermentation, e.g., tapai (local name). Ragi, prepared from a mixture of rice flour, spices, and water or sugarcane juice, naturally contains filamentous fungi, bacteria, and yeast [9,10]. According to Saono et al. [11], ragi contains molds, yeast, and bacteria with

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amylolytic power as well as yeast and bacteria (lactic acid bacteria) with non-amylolytic power. Those with amylolytic power in mold are *amylomyces, mucor,* and *rhizopus*. In yeast, there are *endomycopsis (saccharomyces)* and *candida*, and bacteria contain a kind of *bacillus* [12]. Yeast cultures for ragi originating from Sabah, Malaysia are categorized into species of *Saccharomyces cerevisiae* and *Saccharomycetales sp.* [13]. Application of microbial inoculation that contains yeast in composting has been commonly used in previous studies [14–16]. However, to the best of our knowledge, no studies have been done on the effect of local Sabah ragi on food waste composting. Therefore, the purpose of this study is to investigate and evaluate the performance of food waste composting with the addition of Sabah ragi, as well as to compare the composting performance from previous studies.

2. Materials and methods

In order to investigate and evaluate the performance of food waste composting, optimization of turning frequency and ragi dosage using simulated food waste in compost bottle was studied. The preliminary study includes the investigation of turning frequency every 0, 1, 3, and 5 days for 40 days and different ragi compositions of 0 g (control), 0.5 g, 1.0 g, and 1.5 g ragi/200 g initial compost for 15 days. The optimum conditions obtained were later used for passive aerated in-vessel composting of real food waste in this study (Fig. 1).

2.1. Composting materials

The materials for the optimization consist of simulated food waste and dry leaves with a ratio of 2.6:1 (simulated food waste: dry leaves). The ratio was selected based on a 50 % starting moisture content estimation. Simulated food waste was prepared by mixing vegetables (34 %), bread (29 %), cooked rice (16 %), banana peel (13 %), and cooking oil (8 %). The ratio for each material was estimated based on the typical wasted food composition in Asia reported by Paritosh et al. [17]. The materials used in simulated food waste were bought from a supermarket, while dry leaves were collected within the university landscape area.

A total of 128 kg of food waste and dry leaves (2.6:1 by weight) were used as materials in the composting process. Food waste from local restaurants located in Karamunsing Complex, Kota Kinabalu was gathered and dry leaves (bulking agent) were collected around Universiti Malaysia Sabah (UMS) due to its abundant availability. Before putting food waste and dried leaves into the composter, they were separated from non-compostable materials like plastic. The characteristics of food waste, dry leaves, and mixed waste were displayed in Table 1. About 0.61 kg of local Sabah ragi was added to the compost mixture. In the previous study, Zahrim et al. [18] used food waste and dry leaves (2:1 by weight) as composting materials. Meanwhile, Aji et al. [19] used food waste and unshredded dry leaves (3:1 by weight) as composting materials. The characteristics of the composting materials used can be found in Zahrim et al. [18] and Aji et al. [19].

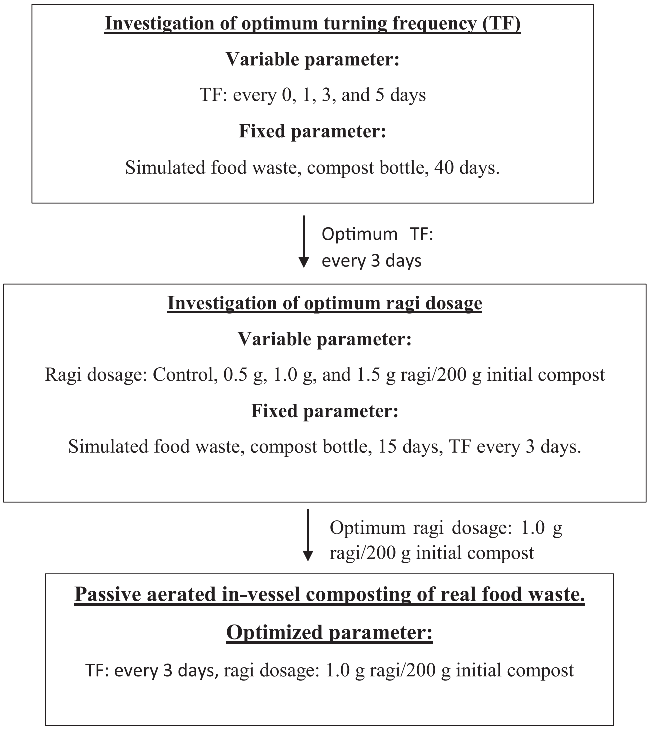

Fig. 1. Overview of the composting process.

2.2. Experiment design and process

The composting process was conducted at the Environmental Lab, Faculty of Engineering, UMS to determine the optimum turning frequency and ragi dosage. The composting process was conducted in 1.5-liter compost bottles for three trials, which was inspired by a previous study by Zahrim et al. [20]. Several turning frequencies were studied, which included turning every 0, 1, 3, and 5 days for 40 days. Based on our previous study, the turning frequency of every 3 days has higher organic matter loss. Several studies also conducted compost turning every 3 days [1,4,21]. The purpose of mixing or turning is to provide microbes with adequate access to substrates, nutrients, and moisture. For determining the optimum ragi dosage, different ragi compositions of 0 g (control), 0.5 g, 1.0 g, and 1.5 g ragi/200 g initial compost were studied for 15 days~~.~~

The composting process using a passive aerated in-vessel composting reactor was conducted at the Faculty of Engineering, UMS. The reactor is designed for a capacity of 850 liters per volume. The reactor has 15 holes in the back wall with a diameter of 2.6 cm to allow natural air circulation. A mixer arrangement is provided at the center of the reactor which is connected to a motor with a gear arrangement. Turning was carried out by switching on the mixer every-three days for 15 min. The composting process lasted for 40 days. In the previous studies by Zahrim et al. [18] and Aji et al. [19], a passive aerated in-vessel reactor was used with a capacity of 1000 liters per volume. Zahrim et al. [18] conducted the composting process with turning once a week. Meanwhile, no turning was performed during the composting process by Aji et al. [19]. Both composting processes were conducted for 40 days. The details of the reactor can be found in Zahrim et al. [18] and Aji et al. [19].

2.3. Analytical methods

Laboratory analyses included moisture content measurements, total organic carbon (TOC), temperature, pH, conductivity, nutrients and pathogens. About 0.5 kg of the compost was collected from 15 different places in the mixture and manually blended. The temperature was taken every day at four different places. The moisture content (MC) of the

Table 1
Characteristics of food waste, dry leaves, and mixed waste.

Parameter	Food waste	Dry leaves	Food waste-Dry leaves
Moisture content (%)	71.9	13.3	61.6
Wet density, kg/m^3	1027	205	553
pH	4.4	5.4	4.8
Electrical conductivity (mS/cm)	6.7	1.6	4.9
Nitrogen, N (%)	1.8	1.4	1.1
Phosphorus, P (%)	0.0125	0.0113	0.0132
Potassium, K (%)	0.0798	0.3360	0.0717
Carbon, C (%)	51.8	50.9	50.3
C/N ratio	29.1	36.6	47.5

sample was evaluated by drying it for 24 h at 105 °C in an incubator (Binder). Equation (1) was used to determine the moisture content percentage. The total organic carbon (TOC) was evaluated by heating oven-dry samples to 550 °C for 4 h in a high-temperature furnace (Thermolyne 46100) [22]. Equation (2) was used to calculate the ash [23], while equation (3) was used to determine the TOC [24]. Equation (4) [25] is used to calculate organic matter loss.

$$\text{MC}\ (\backslash\%)\ =\ )\ = \frac{\text{weight of wet sample-weight of dry sample}}{\text{weight of wet sample}} \tag{1}$$

$$\text{Ash}\ (\backslash\%)\ =\ )\ = \frac{W_{\text{crucible+sample (after burning)}} - W_{\text{crucible)}}}{W_{\text{sample}}} \tag{2}$$

$$\text{TOC}\ (\%) = \frac{\text{Volatile solid}\ (\backslash\%))}{1.8}$$

$$= \frac{100\ \text{- ash}}{1.8} \tag{3}$$

$$\text{OM loss}\ (\%) = 100 - 100\left(\frac{A}{B}\right) \tag{4}$$

where,

$$A = \%\ \text{Initial ash content}\ \times (100 - \%\text{Final ash content})$$

$$B = \%\ \text{Final ash content}\ \times (100 - \%\text{Initial ash content})$$

A 5 g sample of compost was mixed with 50 mL of distilled water to determine the pH and conductivity of the compost. The mixture was stirred for 20 min using a magnetic stirrer before being left for 24 h. The pH and conductivity of the mixture were analyzed using a pH/EC/TSD/°C portable meter after it had been filtered (Hanna Hi 9811–5). By filling a 500 mL beaker with material, the wet density was determined [26]. Dried samples were used for the N, P, and K analyses. Following the Malaysian Standard, nitrogen (N) was evaluated using a protein analysis method [27]. Inductively coupled plasma–optical emission spectrometry was used to determine phosphorus (P) and potassium (K) (ICP-OES). Salmonella and E. coli were identified and counted in compost using a fresh sample. Salmonella counts were calculated using the Australian Standard method [28], while E. coli counts were determined following AS 1766.2.3 [29]. For Salmonella, the specimen was plated onto XLD agar and incubated at 37 °C for 24 h, whereas for E. coli, plates were cultured at 44.0–44.5 °C for 48 h and measured using the MPN method. Samples were delivered to Chemsain Konsultant Sdn Bhd for N, P, K, and pathogen analysis.

Statistical analysis of the data was done through Microsoft Excel 2019 software. The mean and standard deviation of the three replicates were calculated. The data was analyzed using the t-test method for comparison. The level of significance was set at $p < 0.05$.

2.4. Heat energy

Considering the heat energy transferred from the compost to evaporate the moisture content for all composting processes, the equation (5) of heat energy was referred as follows [30,31];

$$q = mC_p\Delta T \tag{5}$$

where;

q = Heat energy from the system (kJ kg^{-1}).

m = mass of compost (kg).

C_p = specific heat capacity of compost material.

ΔT = change in temperature (K).

Heat energy values were calculated using estimated standard specific heat capacity values for compost material (2.844 kJ/$kg^{-1}K^{-1}$), estimated by Irvine et al. [30]. The energy values were calculated on a daily basis and expressed as energy stored in kJ $kg^{-1}day^{-1}$.

2.5. Kinetic studies

In this study, three different types of kinetic models were used: zero order, first order, and second order. The degradation process in terms of total organic carbon (TOC) content during the composting process was monitored to determine the kinetic models. The kinetic model can be derived from Equation (6) [32].

$$\frac{d(\text{TOC})}{dt} = -k(\text{TOC})^n \tag{6}$$

where TOC is total organic carbon (%), superscript “n” represents the equation’s order which can be zero, one, two or any real number and k is the rate constant.

Table 2 shows the mathematical equation, linear equation, and graph plot for each kinetic model. The value of k was calculated as the slope of the fitted straight line, obtained using the linear equation for each case [33]. The coefficient of correlation (R^2) was used to evaluate the quality of the kinetic model fit to the experimental data.

3. Results and discussion

3.1. Determination of the optimum ragi dosage using a compost bottle

The different phases of composting and the relative completion of the composting process were characterized by variations in organic matter content [34]. Organic matter loss patterns in different ragi compositions are presented in Fig. 2. At the end of the process, organic matter losses of 51.8 %, 49.5 %, 61.3 %, and 57.1 % were observed in control, 0.5 g, 1.0 g, and 1.5 g ragi, respectively. From the t-test result, 1 g of Sabah ragi had the highest organic matter loss and was significant compared to other dosages ($p < 0.05$). Meanwhile, 0.5 g has no significant difference ($p > 0.05$) compared to composting without Sabah ragi (control). Therefore, 1 g of ragi was chosen due to the highest biodegradability rate in organic matter compared to other treatments.

Unicellular organisms in ragi are advantageous to ease bacteria’s manipulation and growth capacity [13,34]. Furthermore, an earlier study has shown that adding bacterial agents exogenously is more practical and cost effective [35,36]. Sarkar et al. [14] reported that inoculation of *Geobacillus* in the thermophilic stage could significantly improve the microbial metabolism in composting and speed up the composting process. Another study by Poongodi & Damodharan [16] stated that there were significant effects on the ecological succession of microorganisms and the rate of biodegradation of organic matter during the composting of food waste using yeast sludge as inoculum. According to Manu et al. [37], the higher rate of organic matter degradation for the treatment was due to enhanced microbial activity.

3.2. Temperature and energy values

Fig. 3 shows the comparison with previous studies in compost and the mean ambient temperature during the composting process. The average ambient temperature ranges between 28.6 °C and 33.0 °C. In this study, the initial temperature of the compost was 34.1 °C and rapidly increased to 54.2 °C on day 7. Furthermore, over a four-day period, the temperature remained at a more extended thermophilic

Table 2
Mathematical equation and plots for kinetic models [32].

Kinetic model	Mathematical equation	Linear equation	Plots
zero order	$TOC = -kt + TOC_o$	$TOC = -kt + TOC_o$	TOC versus t
first order	$TOC = (TOC_o)exp^{-kt}$	$lnTOC = -kt + lnTOC_o$	ln TOC versus t
second order	$TOC = \frac{TOC_o}{1 + (TOC_o)kt}$	$\frac{1}{TOC} = kt + \frac{1}{TOC_o}$	1/TOC versus t

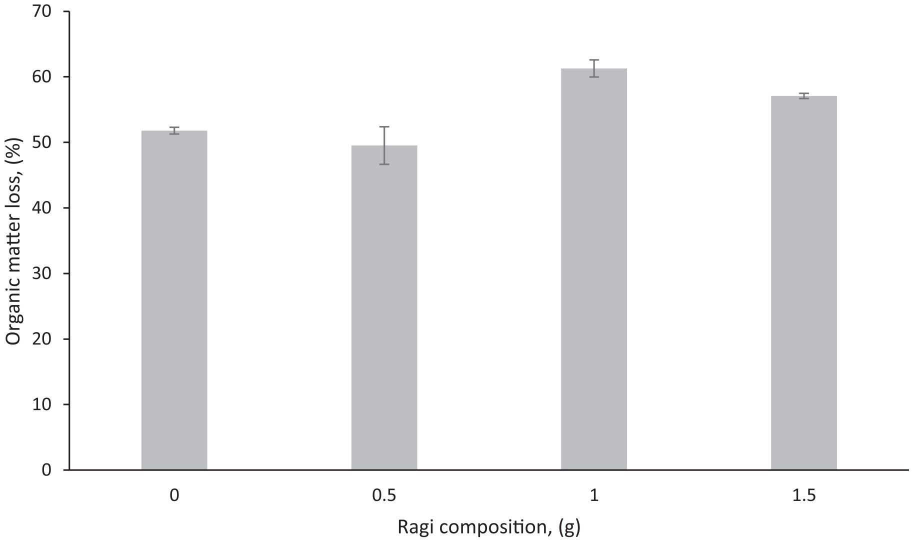

Fig. 2. Organic matter loss in different ragi compositions. Mixture: 0 g (control), 0.5 g, 1.0 g, and 1.5 g ragi/200 g initial compost.

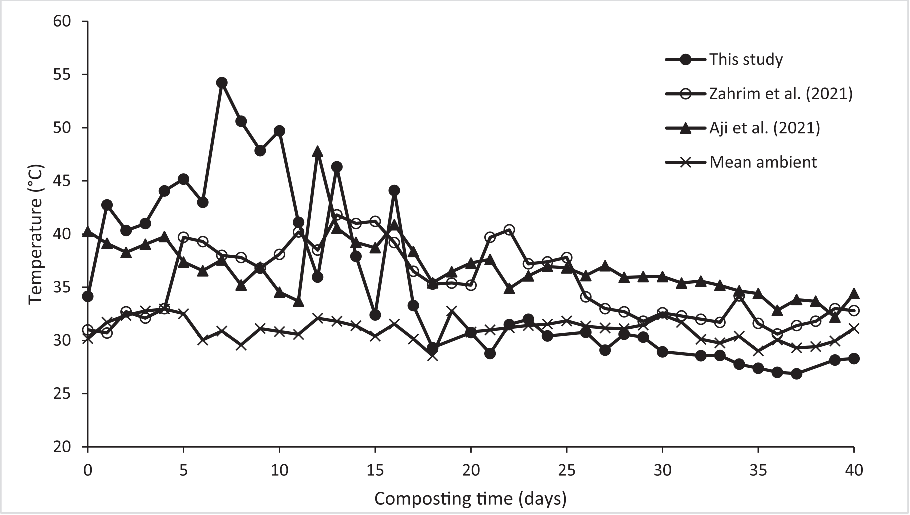

Fig. 3. Comparison of the temperature from this study and previous studies.

temperature (≥45 °C) [38]. The more prolonged thermophilic phase achieved in this study could be due to the addition of ragi that enhanced the microbial activity. The temperature rise is due to the fermentation induced by increased microbial respiration and the availability of organic matter 39. In comparison, Aji et al. [19] achieved a thermophilic temperature (47.8 °C) on day 12 and lasted only one day. Meanwhile, Zahrim et al. [18]] had the highest temperature (41.8 °C) up to the mesophilic phase and did not achieve the thermophilic temperature, usually around 45–75 °C [36]. The low temperature achieved by Zahrim et al. [18] can be explained by excess moisture that hinders the temperature from rising [40]. Nevertheless, the temperature reported by Zahrim et al. [18] achieved the optimum mesophilic temperature for an effective composting process of 35 °C [38]. In addition, thermophiles are essential to further breaking down simple carbohydrates that were initially broken down by mesophiles during the mesophilic phase of the composting process [41]. Also, thermophilic stages are important for speeding up the process and lowering pathogen levels, resulting in a more valuable final product [42].

Subsequently, from day 17 onwards, the compost temperature decreased rapidly to a near ambient temperature of 30 ± 3 °C. This trend shows that the temperature entered the cooling phase faster than others. During the cooling phase, the microbial activity and organic matter decomposition rate have slowed down, and the compost pile's temperature gradually decreases until the end of the composting process [43]. The temperature's subsequent reduction also reflected the depletion of readily biodegradable components [44]. Finally, the cumulative temperature in this study was significantly higher compared to others at the early stage of composting (Fig. 4). The cumulative temperature of this study (686.5 °C) during 15 days of active composting was 13.8 % higher than that of Zahrim et al. [18] (592.0 °C) and 10.4 % higher than that of Aji et al. [19] (614.9 °C). Additionally, the temperature of the composting pile was also related to water evaporation and air convection rate [45]. In the present study, ragi was found to positively affect the thermophilic duration of compost relative to compost that did not contain added ragi.

The results of the energy values obtained using average temperature profiles are shown in Fig. 5 and Fig. 6, where Fig. 5 shows daily energy values and Fig. 6 shows cumulative energy values. In this study, the highest heat generation rate per initial mass of compost dry matter was ~4098 kJ kg^{-1} day^{-1}. This value was higher than that of Zahrim et al. [18] (3544 kJ kg^{-1} day^{-1}) but lower than that of Aji et al. [19] (9650 kJ kg^{-1} day^{-1}). Even though the average temperature for this study was the

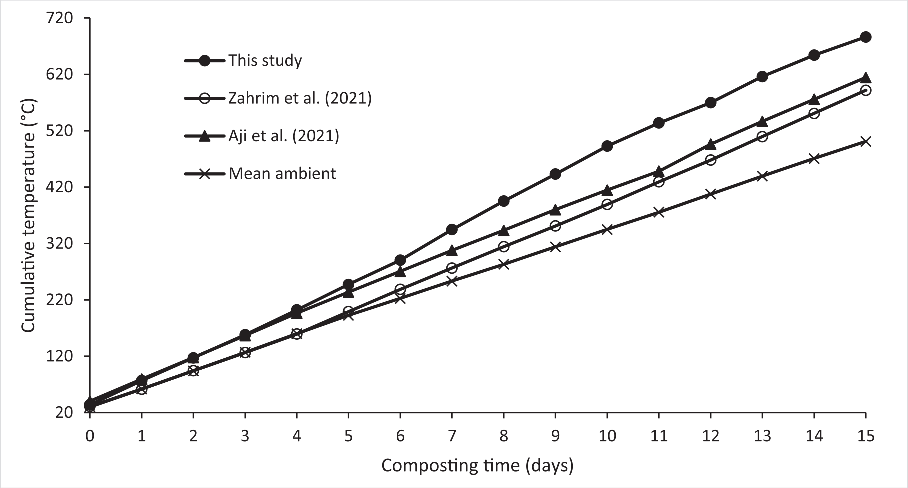

Fig. 4. Comparison of the cumulative temperature from this study and previous studies.

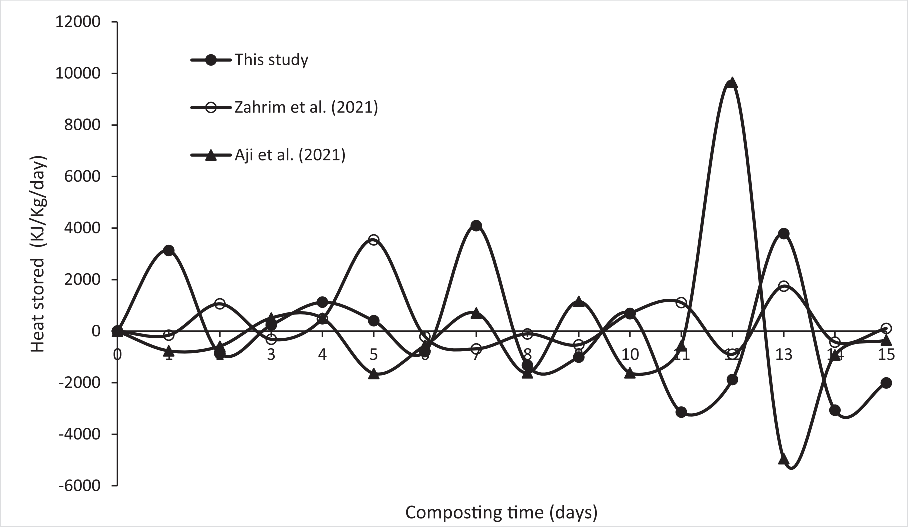

Fig. 5. Comparison of the heat stored from this study and previous studies.

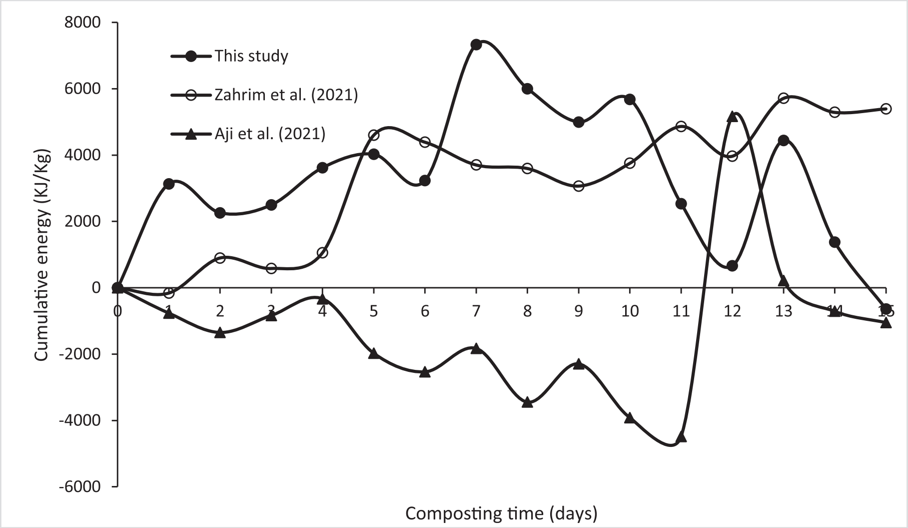

Fig. 6. Comparison of the cumulative energy from this study and previous studies.

highest, the temperature difference was lower compared to the data reported by Aji et al. [19] on day 12, which caused a high value of heat stored on that day. Energy values during composting are also reported by Irvine et al. [30] for sewage sludge and green waste composting (6000 kJ kg^{-1} day^{-1}) and Ekinci et al. [46] for paper mill sludge with broiler litter (2435 kJ kg^{-1} day^{-1}) and by Harper et al. [47] for straw and poultry manure composting (2791 kJ kg^{-1} day^{-1}). Negative values in Fig. 5 can be explained by the fact that overall energy losses exceed energy emitted on those specific days [30].

The cumulative energy levels ranged from approximately −4000 to 7000 kJ kg^{-1} day^{-1}. This value was in the range of the data reported by Mwape et al. [48] for cow manure and green waste (1273 kJ kg^{-1}), and by Harper et al. [47] for paper mill sludge and poultry manure compost (3649 kJ kg^{-1}), and for straw and poultry manure compost (5111 kJ kg^{-1}). They were also lower than those found in sewage sludge and green trash (7000–10 000 kJ kg^{-1}) [25] and for biosolids and wood chips (8092 kJ kg^{-1}) [46]. Low cumulative energy values recorded were due to the excessive temperature drop when the composting process shifted to the cooling phase after 15 days of composting. Moreover, the difference in decomposition rates under various composting settings causes variances in cumulative energy values [30].

3.3. *Moisture content*

The moisture content (MC) of waste material is correlated with physical and chemical properties, acting as a medium for transporting nutrients for microbial activity [37]. The initial MC of the compost from this study, Zahrim et al. [18] and Aji et al. [19], was found to be 61.6 %, 57 %, and 54.6 %, respectively (Fig. 7). The MC was in the recommended range stated by previous researchers that effective composting could be carried out with an initial MC of 50–70 % [49]. The optimum range is favorable to microbial activity and nutrient metabolism while regulating composting temperatures and organic matter degradation [50]. After 40 days of composting, the MC from this study and Aji et al. [19] was reduced to 19.9 % and 15.4 %, respectively. An apparent decrease of MC was observed during the thermophilic phase, causing water evaporation. However, the MC from Zahrim et al. [18] increased throughout the process and had a final MC of 78 %.

According to Manu et al. [37], the sudden decrease in MC could be due to an increased temperature. Higher turning frequencies also led to more significant moisture loss and produced better compost in terms of final moisture content [51]. On the other hand, the increment in MC might be due to the weak effect of vaporization. Additionally, if alcoholic fermentation occurred, a fraction of aqueous compounds such as ethanol, methanol, esters (e.g. acetate) and a variety of carboxylic acids (such as butyric acid) would be created, increasing the wetness of the pile [31,32]. Furthermore, Miller [52] reported that 0.5 to 0.6 g H_2O of metabolic water is produced per gram of volatile solids decomposed, contributing to the moisture increment. Even though Nakasaki et al. [53] mentioned that heat and airflow produced during composting evaporate significantly more water than is produced, possibly a significant amount of the energy is lost as conductive heat loss rather than fully utilized for moisture removal. On top of that, the water absorption capacity of compost materials and initial MC is controlled by the level of MC in the composting process [54]. High MC (above the optimal range) slowed the degradation process by filling the voids, preventing oxygen passage in the compost [54].

3.4. *Total organic carbon*

Fig. 8 depicts the total organic carbon (TOC) during the composting phase from this study and earlier studies. TOC was decreased gradually in all treatments during the composting process. This trend is likely due to carbon loss as CO_2 [55] and continuous biodegradation of organic matter during composting [56]. The TOC for this study, Zahrim et al. [18] and Aji et al. [19], was initially 50.3 %, 48.0 %, and 52.2 %, but was reduced to 37.1 %, 35 %, and 42.5 %, respectively, by the end of the composting process. The TOC profiles in all processes followed the previous trend reported by Soto-paz et al. [7] that rapid decreases in TOC were achieved during the active stage of the process (mesophilic and thermophilic phase). The degradation process mainly progresses during the mesophilic and thermophilic stages, involving numerous microorganisms. It can be observed that the biodegradation performance was greater in the process with the turning mechanism. Similarly, Getahun et al. [55] and Ogunwande et al. [57] reported decreased carbon content with increasing turning frequency. Moreover, proper environmental conditions are favorable for microbial degradation. In addition, excessive or less aeration can significantly influence the degradation of organic matter by reducing the heat and moisture of the material, resulting in nutrient loss and poor final product quality [51].

3.5. *Kinetic modelling of total organic carbon degradation profiles*

Kinetic modelling is crucial in predicting the composting process based on mathematical models. In this kinetic analysis, the relative completion time of the composting was assumed to be reached whenever the temperature difference between the compost and the ambient temperature was lower than 3 °C for three consecutive days. Therefore, the process that has not yet met the requirement was considered to be in an active phase. Based on the experimental data, this study and Aji et al.

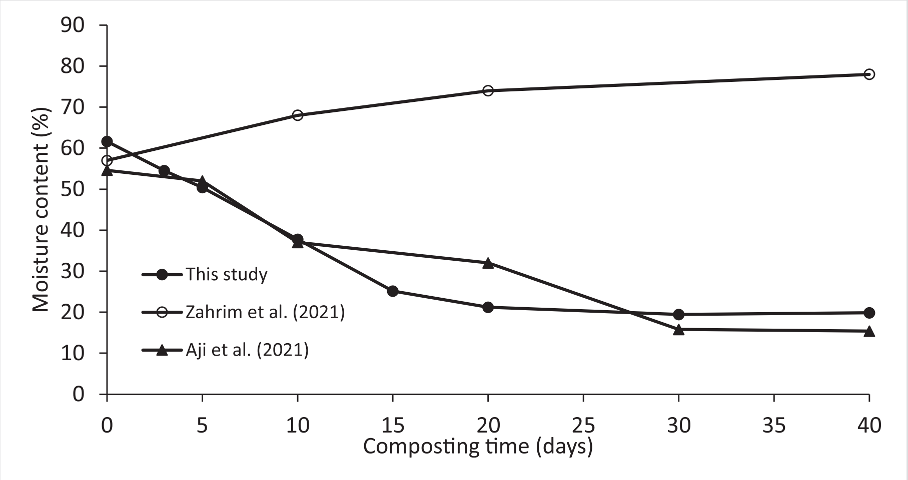

Fig. 7. Comparison of the moisture from this study and previous studies.

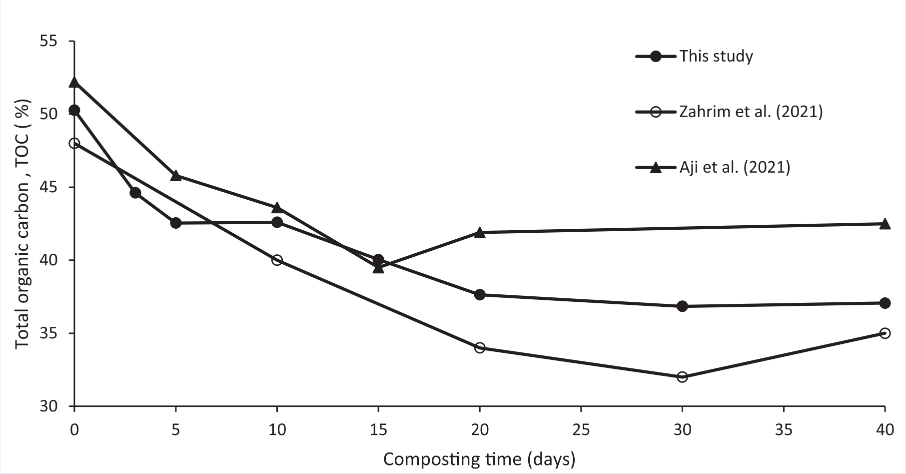

Fig. 8. Comparison of the total organic carbon from this study and previous studies.

[19] satisfied the conditions stated after day 20, while Zahrim et al. [18] had reached completion after day 30 of the composting process. Hence, the kinetic analysis was considered only for the data that lies in the active composting phase.

Based on the elementary kinetic modelling technique, the TOC profiles for this study, Zahrim et al. [18] and Aji et al. [19] followed the second-order kinetic equation. Second-order kinetics were a good fit for the TOC degradation, with the highest value of R^2 compared to other models. On the other hand, the R^2 for the zero- and first-order kinetics was much lower for all processes. The values for the correlation coefficient (R^2) and rate constant, *k,* are summarized in Table 3. The degradation rates are affected by the composting time, compost pile area, and product and are significant for optimizing or designing a composting system. The rate constant, *k* value for this study was approximately similar to that of Aji et al. [19], while the *k* value from Zahrim et al. [18] was slightly higher. A higher degradation rate might be due to enhanced microbial activity from the turning mechanism. According to Zhang et al. [58], turning could enhance the breakdown and conversion of phytotoxic substances and facilitate compost maturation. Moreover, a longer active phase was observed in the data reported by Zahrim et al. [18], which might lead to higher TOC degradation. Several studies also found that second-order better predicts the degradation profile during composting, as illustrated in Table 3.

It should be noted that the rate constant was affected by the aeration technique. From Table 3, the k value was significantly higher with forced aeration, followed by processes that possess turning mechanisms, and passive aeration with static mode has the lowest k value. Forced aeration and regular turning accelerate the composting process by improving aeration throughout the heap [7]. Furthermore, turning and microbial inoculation aid in the degradation of organic materials by increasing the activity of microorganisms [35]. Application of enzymes also has the positive effect of easily degrading lignocellulosic materials [59]. For passive aeration without a turning mechanism, the degradation kinetics could be improved by the addition of a bulking agent to food waste during composting. Suitable bulking agents give structural support, absorb moisture, promote aeration, adjust the appropriate carbon–nitrogen ratio and facilitate the homogeneous and efficient completion of the compost reaction, resulting in high-quality end products [54].

Producing matured compost from food waste remains challenging for several reasons related to its characteristics, which are highly variable depending on its composition. Food waste composition also depends on the source and consumption habits. Furthermore, food waste is influenced by the collection and sorting system, which by the initial non-organic content determines the impurity level at the end of the process [60]. Besides, aeration, temperature, moisture content, pH, and other environmental factors affect the composting process's effectiveness, and the turning mechanism is crucial to regulating mass and heat exchange [61].

From Table 3, the initial EC values varied from 0.4 to 9.4 mS/cm. The EC values reflected the salinity levels of the compost. Liu et al. [62] also reported a low initial EC for food waste of 0.5–0.9 mS/cm. Wong et al. [63] stated that the compost would be safe to use for planting when the EC value was less than 4 mS/cm. Compost with low EC can be used directly, while compost with high EC must be mixed well with soil or other materials with low EC before it can be used for growing crops [64]. Other researchers also reported high initial EC values during food waste composting, ranging from 7.2-10.3 mS/cm [65,66].

3.6. pH and electrical conductivity

pH is one of the critical parameters impacting biochemical activities that allow mineral solubility and nutrient bioavailability for microorganisms [69]. Fig. 9 shows the changes in pH during the composting process. The initial pH for all processes was acidic, ranging from 3.2 to 4.9. Subsequently, the pH for all processes was in the range of 7.1–7.3 by the end of the composting process. Makan et al. [69] mentioned that the pH value of waste that contains food waste is slightly acidic during the initial stage. Similarly, several studies reported low pH during the early stage of food waste composting; pH values of 4.0–5.1 [4,8,56]. During the early stages, the formation of organic acids under the action of microbial activities decreases the pH, which is responsible for hindering microbial activities and the decomposition process [70]. Meanwhile, the increase to neutral is due to acid consumption and ammonia production [69]. Increasing pH during composting and eventually stabilizing at pH 7–8 indicates a well-established composting process [71]. Moreover, pH variation affects the phytotoxicity of the compost due to acidic conditions (<5.5) and ammonia presence (>8.5) [72].

The electrical conductivity, EC, reflects the salinity of the composting matrix [73] and its appropriateness for crop growth [74]. The initial values for EC for this study, Zahrim et al. [18] and Aji et al. [19] were 4.9 mS/cm, 0.4 mS/cm, and 8.9 mS/cm, and had a final EC of 3.8 mS/cm, 0.9 mS/cm, and 7.3 mS/cm, respectively. The compost is safe to use for planting when the EC value is less than 4 mS cm^{-1}. Hence, it was suggested that for EC values exceeding 4 mS cm^{-1}, aeration strategies should have been optimized according to different stages of composting [75].

Table 3
Comparison of type of aeration, rate constant, *k*, and correlation coefficient, R^2 for second-order kinetic model for food waste composting.

Amendment	Inoculation	Aeration	Turning frequency	Composting time (days)	Effective volume (L)	Initial conditions				Highest temperature (°C)	OM loss (%)	*k*, $TOC^{-1} \cdot day^{-1}$	R^2	Reference
						C/N	MC (%)	pH	EC (mS/cm)					
Dry leaves	Sabah ragi	Passive	3 days	20	850	47.5	61.6	4.8	4.9	54.2	77.8	0.00030	0.8863	This study
Dry leaves	NA	Passive	Once a week	30	1000	NA	57.0	3.2	0.4	41.8	78.6	0.00040	0.9870	[18]
Dry leaves	Recycled compost	Passive	NA	20	1000	27.2	54.6	4.9	9.4	47.8	74.7	0.00030	0.8877	[19]
Pruned elm tree branches and sheep manure	NA	Passive	NA	30	75	27.0	65.0	6.9	2.4	63.0	83.6	0.00020	0.9451	[32]
Yard trimmings and sawdust	Fungal strain (*Phanerochaete chrysosporium*)	Passive	NA	60	NA	20.5	60.0	5.7	5.6	NA	47.0	0.00004	0.7508	[67]
Green waste and rice husk	NA	Forced	NA	12	120	19.6	60.0	4.0	NA	68.0	59.1	0.00070	0.8919	[68]

NA: not available.

3.7. Nutrient value

The nutrients N, P, and K are essential for plant growth. In the present study, the initial N, P, and K were 1.060 %, 0.013 %, and 0.072 %, which eventually increased to 3.98 %, 0.07 %, and 0.23 %, respectively, as shown in Table 4. In this study, total nitrogen was higher than in Zahrim et al. [18] and Aji et al. [19]. The increased nitrogen content in this study could be attributable to a higher net loss of dry weight. Mishra & Yadav [76] found that treatments with more organic matter had a higher net loss of dry weight, resulting in an increase in nitrogen content compared to treatments with less organic matter. For agriculture, compost must have more than 1 % total nitrogen in order to fertilize.

Microorganisms consume phosphorous for their metabolism during the degradation of composting materials. Meanwhile, potassium is required to produce proteins and carbohydrates and regulates water levels within plant cells [8]. The final concentration of phosphorous and potassium is shown in Table 4. The value indicated that the concentration had increased compared to the initial value. Nevertheless, the values for P and K in this study were not in the range recommended by Fan et al. [77]. This may be because the initial compost P and K levels were lower than in other studies [18]. Manyapu et al. [34] suggest that external sources of P and K should be added to finished compost to balance the nutrient content.

The C/N ratio is a critical indicator of final compost quality and its suitability for plants. Microbes use carbon as an energy source and nitrogen to form cell structures [78]. In this study, the C/N ratio after the composting period was 9.3. The C/N ratio was close to the value stated by Zahrim et al. [18], which was ~ 9. These values were lower compared to Aji et al. [19]. A higher C/N ratio might be due to the no-turning mechanism performed in the study by Aji et al. [19]. Mishra & Yadav [76] explained that the loss of dry weight resulted in a greater reduction in total organic carbon and an increase in total nitrogen. However, the value reported was still in an acceptable range, and a value of less than 15 is considered mature compost [76]. In addition, the C/N ratio of finished compost is desired to be close to 10/1 [79].

3.8. Pathogen

The pathogen level in compost must be properly controlled before application as a soil amendment to avoid risk to humans, soil, crops, and the environment. *Salmonella spp.* and *E. coli* are the most common indicators for assessing the presence of pathogens in compost [81]. *Salmonella spp.* were not found in 25 g of compost in this investigation. However *E. coli* was identified at 4 MPN/g by the end of the composting process. According to Manu et al. [[82]], a waste stream should be kept at 55 °C or higher for three days to kill pathogens during the composting process. Another study also reported the presence of *E. Coli* in the final compost for in-vessel food waste composting range of 7.5–51 MPN/g [8,19,83], as shown in Table 5. In this study, the compost contained no *Salmonella spp.* This result suggests that Salmonella spp. were removed entirely during the process, or the initial composting materials might be less likely to be contaminated by *salmonella spp*. Meanwhile, Cekmecelioglu et al. [83] reported the presence of Salmonella during composting of food waste, cow manure and bulking agent. A high level of pathogens might be due to the contamination at the source that contains manure [8]. Moreover, the uncertain level of *E. coli* and *Salmonella spp.* might be due to the inconsistent temperature achieved during composting. In addition, temperatures between 50–60 °C may not always suggest complete sanitization of the final compost since other parameters such as moisture content, nutrient availability, and competing microbiota might influence *E. coli* or *Salmonella spp.* growth [84].

3.9. Techno-economic assessment

Tapai is a popular Malaysian delicacy, generally consumed as a dessert [87]. In Sabah, tapai is a well-known indigenous fermented

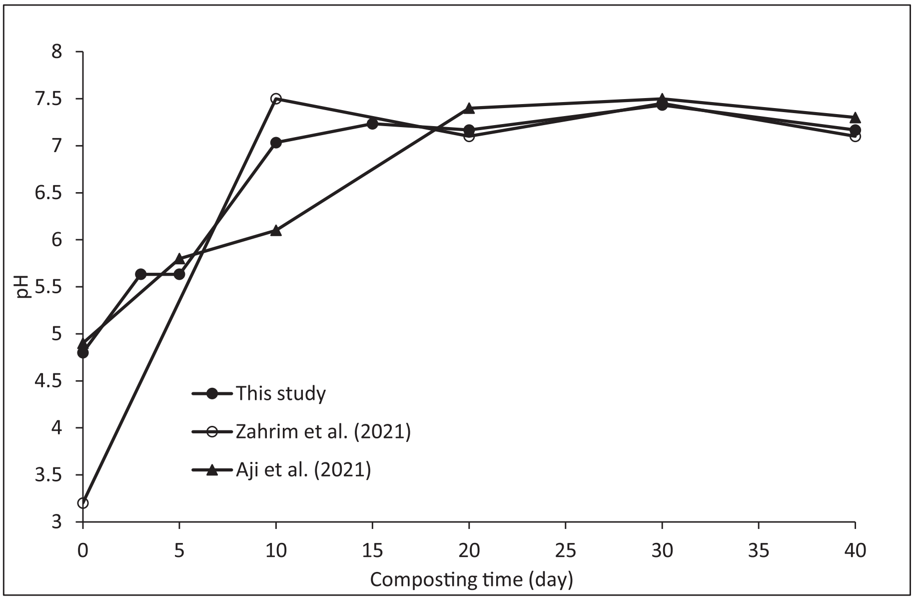

Fig. 9. Comparison of the pH from this study and previous studies.

Table 4
Comparison of nutrient content for food waste composting.

	This study	Zahrim et al. [18]	Aji et al. [19]	Malakahmad et al. [79]	Manyapu et al. [34]	Malaysia SIRIM MS 1517:2012 Standard (Keng et al. [80])	Recommended range (Fan et al. [77])
Nitrogen, N (%)	3.98	2.5	2.6	1.80	0.91	> 1.5	> 1.0
Phosphorus, P (%)	0.07	0.003	1.1	1.70	0.86	NA	0.6 – 1.7
Potassium, K (%)	0.23	0.005	0.8	1.65	0.05	NA	0.4 – 1.1
C/N ratio	9.31	9.14	12.2	20	22.57	<25.0	≤ 25.0

Table 5
Comparison of pathogen level of Salmonella spp and Escherichia coli for food waste composting.

	Salmonellae spp	*Escherichia coli*
This study	Absent in 25 g	4 MPN/g
Aji et al. [19]	Absent in 25 g	51 MPN/g
Fan et al. [8]	Absent	7.5 MPN/g
Cekmecelioglu et al. [83]	44 MPN/g	43 MPN/g
US EPA 503 (Gurtler et al. [85])	< 4 MPN/3 g	NA
UK Composting Standard (Sunar et al. 86)	Absent	< 1000 CFU/g
European standard (Brinton, [72])	Absent in 25 g	< 1000 MPN/g

Table 6
Cost of ragi utilization as additive for compost and tapai production.

Compost		Tapai	
Price 1 kg ragi	RM 60.00	Price 1 kg ragi	RM 60.00
Ragi used for 128 kg composting material	0.61 kg	Ragi used for 1 kg tapai (1 % by weight)	0.01 kg
Price 0.61 kg ragi used	RM 36.60	Price 0.01 kg ragi used	RM 0.60
Final weight of biodegraded compost after 40 days	30.00 kg	Selling price 1 kg tapai	RM 20.00
Selling price 1 kg compost	RM 6.00	Price of ragi used every 1 kg tapai	RM 0.60
Weight of ragi used every 1 kg compost	0.02 kg	Gross profit for 1 kg tapai produced	RM 19.40
Price of ragi used every 1 kg compost	RM 1.22		
Gross profit for 1 kg compost produced	RM 4.78		

RM: Ringgit Malaysia.

alcoholic beverage among Kadazan-Dusun-Murut (KDM) ethnics during festive occasions and gatherings [88]. Currently, tapai production using ragi as a fermentation starter is commercially produced on a small scale. Hence, the amount of ragi and tapai produced in Sabah is still unknown. Table 6 shows the estimated cost for compost and tapai production using ragi as an additive.

Utilization of ragi as a fermentation starter for tapai production is clearly more profitable. However, the total cost of ragi used in this study is still covered by the value of the final compost. Moreover, due to its positive effect, the application of ragi as a fermenter can be expanded for the composting process. The success of this study becomes an essential factor for the potential large-scale commercial production of ragi as an additive for the composting process.

4. Conclusion

Our study has shown that *Sabah ragi* can be effectively used to enhance the thermophilic phase during food waste and dry leaves composting. The addition of *Sabah ragi* enhanced the role of microbial metabolism, which is responsible for active organic matter degradation during the composting process. The result from the temperature profile has shown a significant difference compared to the composting that has no ragi inoculation. The highest temperature recorded at 54.2 °C on day

7. A compost temperature of more than 45 °C was observed continuously for 4 days, indicating a longer thermophilic phase. The highest heat generation of 4098 kJ kg^{-1} day^{-1} achieved on day 7. After 15 days, the heat generation gradually dropped, indicating that the composting process had shifted to the cooling phase. On day 40, the moisture content was 19.9 %, with pH and EC values of 7.2 and 3.8 mS/cm, respectively. The salinity level (EC) of the final compost was below the salt content limit, making it suitable for agricultural use. In terms of organic matter degradation, TOC reduction of 26.2 % and OM loss of 77.8 % were observed at the end of the composting process. Kinetic analyses based on the TOC profile have shown that the degradation followed the second-order kinetic with 0.0003 $TOC^{-1}.day^{-1}$. Therefore, the application of the second-order model resulted in good responses for predicting the composting progress. The composting time was completed after 20 days of active composting. After 20 days, the composting process has entered the cooling phase based on the low temperature difference between the ambient and composting temperatures. The pathogen results met the limit and the N, P, and K values were 3.98 %, 0.07 %, and 0.23 %, respectively. An estimated ragi cost of RM 1.22 was required to produce 1 kg of compost with a selling price of RM 6.00/ kg of compost, resulting in a gross profit of RM 4.78/ kg of compost produced. The utilization of *Sabah ragi* as an inoculant in food waste and dry leaves composting has a positive effect on the compost temperature enhancement. The presence of necessary microorganisms from ragi inoculation could improve the stability and maturity of the composting materials. However, further research is needed to test the compost for phytotoxicity and plant growth.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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