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FOOD WASTE-DRY LEAVES COMPOSTING: MIXTURE FORMULATION, TURNING FREQUENCY AND KINETIC ANALYSIS

Mohd Al Mussa Ugak, Nur Aqeela Syuhadah Aji, Abu Zahrim Yaser*, Junidah Lamaming, Mariani Rajin and Sariah Saalah

Chemical Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia

*Corresponding author: Abu Zahrim Yaser Email: zahrim@ums.edu.my

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ABSTRACT. *Composting is a controlled biological process that converts organic matter into soil conditioner and kinetic modelling is necessary to design the composting system. The aims of this study are to determine the optimum compost mixture and turning frequency for food waste and dry leaves composting, as well as to evaluate an elemental kinetic model based on volatile solids (VS). The elemental kinetics of the process were determined using pseudo zero-, first-, second- and n-order equations. Three different feedstock mixtures were used, namely 40% FW (Mix A), 60% FW (Mix B) and 80% FW (Mix C). Four sets of experiments (TF for every 0, 1, 3, and 5 days) were conducted to investigate the turning frequency (TF). The composting process was carried out in a compost bottle for 40 days. Based on organic matter loss, Mix B and C had the highest OM loss, indicating an acceptable initial compost mixture. The turning frequency of every three days resulted in the highest organic matter loss. Kinetic analysis was performed using coefficient correlation (R^2), root mean square error (RMSE) and modelling efficiency (EF). Application of the second-order model resulted in good responses for compost mixture Mix B and C. Meanwhile, the n-order model successfully estimated the VS changes for the 3-days TF.*

KEYWORDS. Compost, soil conditioner, modelling, second order, n-order

INTRODUCTION

Proper treatment of food waste is a challenge faced by any developing nation, as unmanaged food waste contributes to adverse environmental impacts (Cerda et al., 2018). Globally, around 1.13 million tons of food waste is discarded daily (Chen et al., 2020; Nguyen et al., 2020), which is expected to increase due to population growth (Nguyen et al., 2020). In Malaysia, an estimated 33,000 tons of solid waste are generated daily, with food waste accounting for approximately 44.5 % of the total (SWCorp, 2020). Moreover, food waste accumulation in landfills or incineration drives negative impacts such as greenhouse gas (GHG) emissions and groundwater contamination (Chen et al., 2020). Composting is an environmentally friendly and cost-effective approach that can replace t organic waste processing (Ajmal et al., 2020).

Composting occurs under biological processes carried out under optimum conditions to produce a high quality and stable compost that is nutrient-enriched soil amendment (Waqas et al., 2018). It has long been recognized that biofertilizers produced from food waste can be used as a soil conditioner to reduce chemical fertilizers, enhance soil quality, and rehabilitate polluted soil (Cerda et al., 2018; Yang et al., 2019). However, suboptimal techniques performed in composting cause a lengthy process and possibly produce immature compost (Fan et al., 2016). Therefore, it is critical to regulate composting efficiency by assessing the substrate's biodegradation rate and enhancing the decomposition rate (Malamis et al., 2016).

Initiative on improving better composting procedures to shorten organic matter degradation has been increasing. However, food waste has certain limitations as a biowaste, such as a low C/N ratio and high moisture content. This will inhibit microbial activity and low degradation effectiveness. It can be fixed through the addition of a bulking agent. Fei-Baffoe et al. (2016) suggested that 3:1 was the best ratio of organic solid waste and sewage sludge. Kamaruddin et al. (2018) also studied the effects of different feedstock ratios on the decomposition of green and brown waste. The authors found that a 3:1 ratio of green waste to brown waste produces better compost compared to 1:1 and 2:1 feedstock ratios. Zhou et al. (2018) used a mixture of food waste, sawdust and Chinese medicinal herbal residue with three different ratios (5:5:1, 2:2:1 and 1:1:1) to evaluate the effect on the composting process. The authors mentioned that a ratio of 1:1:1 had the highest germination index (157.3%), a C/N ratio of 16.0, an electrical conductivity below 4 mS/cm and the highest organic reduction (67.2%).

Aeration also affects the composting process. Aeration can be provided through turning or convection for passive aeration systems and through blowers or air pumps for active aeration systems. Varma et al. (2018) discussed how the agitation and aeration rate in composting will affect the microbial activity. Optimum turning frequency (TF) provides sufficient ventilation, which controls the compost pile's temperature, excess water, and microbial activity (Liu et al., 2020). Low or excessive turning frequencies cause slow biodegradation due to undesired porosity, oxygen availability, and heat loss (Soto-paz et al., 2019; Zhang et al., 2019).

Several successful studies have proposed different TFs for different composting materials. For example, Zhang et al. (2019) evaluated the effect of different TF (every 5, 7, 10 and 15 days) on goat manure combined with Camellia oleifera shell. The results showed that turning every 7 days produced high quality compost in terms of total nutrients and C/N ratio. Another study performed by Manu et al. (2019) investigated the influence of TF (every 5 days) and microbial addition on food waste mixed with garden waste. A similar household-scale study with different TFs (every 1, 2, and 3 days) with a C/N ratio of 20, 25, and 30 using food waste and dry leaves was carried out by Nguyen et al. (2020). They concluded that the optimum conditions for plant growth were a C/N of 30 and a turning frequency of once every 2 days.

The above overview data are in agreement with the statement reported by Nguyen et al. (2020) in which, TF and C/N or mixing ratio are dependent on the input materials and bulking agents. In spite of the broad study of mixing ratio and TF, most of the studies just focused on individual factors, with few studies on the influence of both techniques on the same materials and operational conditions. Furthermore, most modern composting facilities focus on the enhancement of degradation of organic matter in the waste to comply with strict market demands and tight environmental legislation (Hamelers, 2004; Hamoda et al., 1998). Composting process kinetics provide useful information about process progress to improve composting operations (Ebrahimzadeh et al., 2017; Hamoda et al. 1998). Therefore, this study investigates and evaluates the effects of various mixing ratios and different TFs on food waste and dry leaves composting and its kinetic degradation profile.

MATERIALS AND METHODS

Materials

Simulated food waste (FW) and shredded dry leaves are used as feedstocks in the composting process. A mixture of 40% FW (Mix A), 60% FW (Mix B) and 80% FW (Mix C) (by weight) was used for determining the optimum compost mixture. Meanwhile, 72% of simulated food waste mixed with dry leaves was used in determining the optimum turning frequency. Simulated food waste was prepared by mixing vegetables, bread, cooked rice, banana peel and cooking oil with the following ratio: 34%, 29%, 16%, 13%, and 8%, respectively. The ratio for each material was estimated based on the typical wasted food composition in Asia reported by Paritosh et al. (2017). The materials used in simulated food waste were bought from a supermarket while dry leaves were collected within the university landscape area.

Experimental Set-Up and Design

A composting study was conducted at the Environmental Lab, Faculty of Engineering (FKJ), Universiti Malaysia Sabah, located in Sabah, Malaysia. The composting process was carried out using 1.5 L compost bottle. The compost bottle design was inspired by a previous study by Zahrim et al. (2020). The compost bottle has a total of 20 holes (equally spaced) around the bottle for maintaining aerobic condition and one hole at the bottom for leachate. During the composting process, the top opening of the compost bottle was closed and sealed using adhesive tape. The mixture was manually mixed before being put into the compost bottle. Figure 1 shows the design of the compost bottle.

For determining the optimum mixture, three different food waste: dry leaves mixtures were used, namely Mix A, Mix B, and Mix C. Four sets of experiments (TF every 0, 1, 3, and 5) were conducted to investigate turning frequency (TF). Each experiment was carried out in 3 trials simultaneously. The composting process lasted for 40 days. For turning, the sample was rotated to make sure the compost was mixed together and subjected to change, causing the top portion of the compost to move to the central portion.

a) b) c)

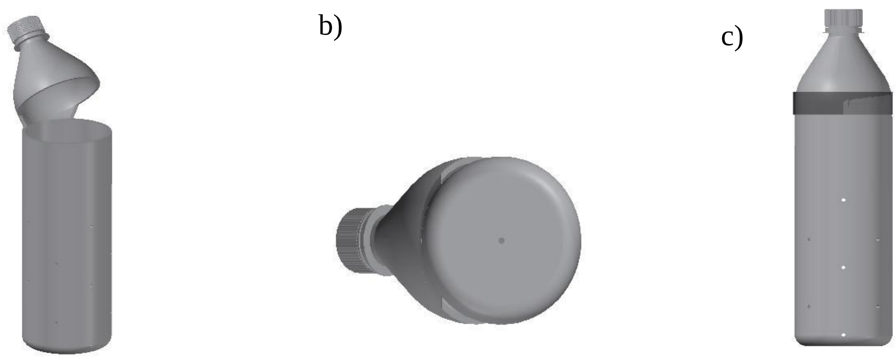

Figure 1. The a) front, b) bottom view of opened compost bottle and, c) front view of closed compost bottle using adhesive tape

Volatile solid (VS) is determined by burning the oven-dry samples using a high-temperature furnace (Thermolyne 46100) at 550 °C for 4 h (APHA, 1985). The ash was calculated using equation (1) (Zahrim et al., 2019), the VS was calculated using equation (2) (Liao et al., 1994) and the organic matter (OM) loss is determined using equation (3) (Paredes et al., 2000);

$$Ash\ (\%) = \frac{W_{crucible + sample\ (after\ burning)} - W_{crucible}}{W_{sample}} \tag{1}$$

$$\begin{aligned} TOC\ (\%) &= \frac{Organic\ matter\ (\%)}{1.8} \\ &= \frac{Volatile\ solid\ (VS)\ (\%)}{1.8} \\ &= \frac{100 - ash\ (\%)}{1.8} \end{aligned} \tag{2}$$

Where TOC is total organic carbon.

$$OM\ loss\ (\%) = 100 - 100\left(\frac{A}{B}\right) \tag{3}$$

where,

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

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

Kinetic Studies

In this study, four different types of kinetic models were used: pseudo-zero order, pseudo-first order, pseudo-second order, and n-order models. The degradation process in terms of volatile solids (VS) content during the composting process was monitored to determine the kinetic models (Baptista et al., 2010). Generally, VS changes are commonly used to determine the level of feedstock degradation (Ebrahimzadeh et al., 2017; Kulcu, 2016). The kinetic model can be derived from Equation (4) (Ebrahimzadeh et al., 2017).

$$\frac{d(VS)}{dt} = -k(VS)^n \tag{4}$$

Where VS is volatile solids (%), superscript "n" represents the equation's order which can be zero, one, two or any real number and k is the rate constant.

Table 1 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 a linear equation for each case (Hamoda et al., 1998).

Table 1. Mathematical equation and plots for kinetic models (Ebrahimzadeh et al., 2017)

Kinetic model	Mathematical equation	Linear equation	Plots
Pseudo-zero order	$VS = -kt + VS_o$	$VS = -kt + VS_o$	VS versus t
Pseudo-first order	$VS = (VS_o)exp^{-kt}$	$ln\, ln\, VS = -kt + ln\, ln\, VS_o$	ln VS versus t
Pseudo-second order	$VS = \frac{VS_o}{1 + (VS_o)kt}$	$\frac{1}{VS} = kt + \frac{1}{VS_o}$	1/VS versus t
n-order	$VS = \sqrt[n-1]{\frac{(VS_o)^{n-1}}{1 + (VS_o)^{n-1}(n+1)kt}}$	$\frac{1}{(VS)^{n-1}} = (n-1)kt + \frac{1}{(VS_o)^{n-1}}$	1/[VS]^(n-1) versus t

Evaluation of kinetic model

The quality of the kinetic model fits to the experimental data was evaluated by the coefficient correlation (R^2), root mean square error (RMSE) and modelling efficiency (EF). These parameters were calculated by equations (5), (6), and (7), respectively, as follows (Ebrahimzadeh et al., 2017; Kulcu, 2016; Petric et al., 2012).

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(X_{obs} - \underline{x}\right) . \left(Y_{model} - \underline{y}\right)}{\sum_{i=1}^{n} \left(X_{obs} - \underline{x}\right)^2 . \sum_{i=1}^{n} \left(Y_{model} - \underline{y}\right)^2} \right)^2 \quad (5)$$

$$EF = 1 - \frac{\sum_{i=1}^{n} (X_{obs} - X_{model})^2}{\sum_{i=1}^{n} \left(X_{obs} - \underline{X}_{obs}\right)^2} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_{obs} - X_{model})^2}{n}} \quad (7)$$

where X_{obs} and Y_{model} are values of observed and estimated data, x and y the mean of observed and predicted data, respectively. For model efficiency (EF), X_{model} is the model value, and X_{obs} is the mean value of observed data. For RMSE, X_{model} is modeled value.

RESULTS AND DISCUSSION

Organic Matter (OM)

The different phases of composting and the relative completion of the composting process were characterized using variations in OM content (Manyapu et al., 2018). Organic matter (OM) was decomposed into volatile compounds and lost from the solid compost during composting (Hu et al., 2009); thus, OM will decrease throughout the composting process. Figure 2 shows the final OM loss of the composting process for different mixing ratios. The OM loss for Mix A, Mix B, and Mix C on day 40 were 44.5%, 79.9% and 78.7%, respectively. Higher OM loss was observed in Mix B and Mix C. This finding is in accordance with findings reported by Guidoni et al. (2018). A higher reduction of OM was observed in a mixture rich with food waste than in a mixture rich with bulking agents. Neugebauer and Sołowiej (2017) also suggested that at least 40% of the bulking agent needs to be composted with kitchen waste for the best results. Several studies showed positive results while using a feedstock ratio of between 60% and 80% FW during composting. Kamarudin et al. (2018) recommended the 75% of food waste be composted with yard and garden waste. In another study, the compost produced from food waste and yard waste with 80% FW (by weight) using a passive-aerated static pile has an acceptable pH (6.6), NPK value (2.4%,2.8%,0.2%) and MC (29.5%) but a high EC value (24.9 mS/cm) (Ng et al., 2021).

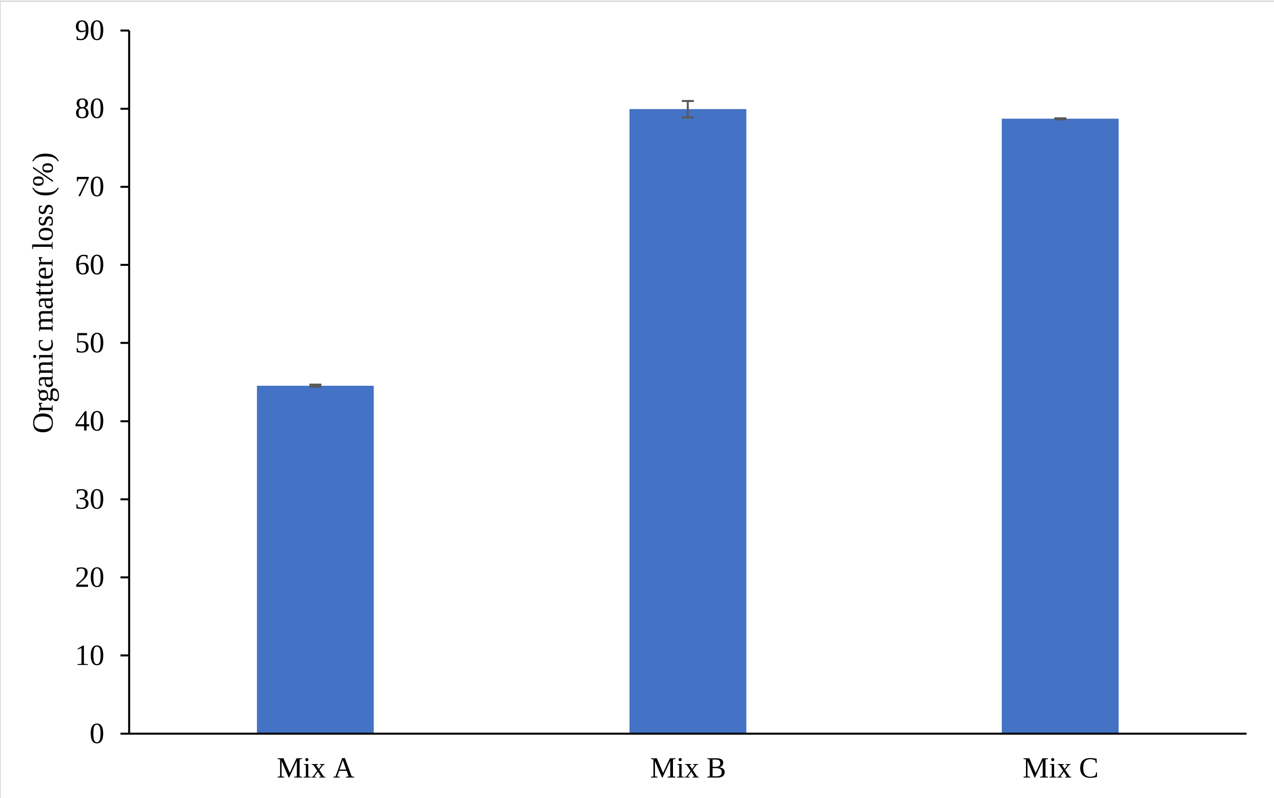

Figure 2. Organic matter loss on day 40 bottle composting under different feedstock proportion (Mix A = 40% FW, Mix B = 60% FW, and Mix C = 80% FW)

The highest OM degradation level was obtained in TF 3, followed by TF 2, TF 4, and TF 1 (Figure 3). Theoretically, increasing turning frequency will result in a higher decrease in organic carbon content (Nguyen et al., 2020). This trend also agrees with the previous study by Soto-Paz et al. (2019). Lack of required oxygen causes a low biochemical degradation reaction rate (Zhao et al., 2012). At the end of the process, organic matter loss of 61.45%, 69.75%, 79.23% and 63.15% were observed for TF 1, TF 2, TF 3, and TF 4, respectively. The result shows that each turning frequency resulted in a significantly different degree of organic decomposition, and TF 3 had higher OM loss than other treatments. The faster organic matter degradation rate was due to enhanced microbial activity for the treatment (Manu et al., 2017). The slow biodegradation in other treatments can be explained by the unfavourable turning frequency. Kalamdhad and Kazmi (2009) reported that 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. Therefore, TF should be adequately controlled for an efficient composting process. Several studies also suggested a 3-days TF during composting. However, TF depends on the initial condition of input materials and bulking agents (Nguyen et al., 2020). Nguyen et al. (2020) reported that 3-day TF was suitable during food waste and dry leaves composting with an initial C/N ratio of 25. Trisakti et al. (2017) suggested that the best result was obtained at 3-day TF during composting of empty fruit bunches with activated liquid organic fertilizer. Meanwhile, Jiang-ming (2017) recommended TF once every 2-4 days when composting pig manure and fungus residue to obtain a stable final compost.

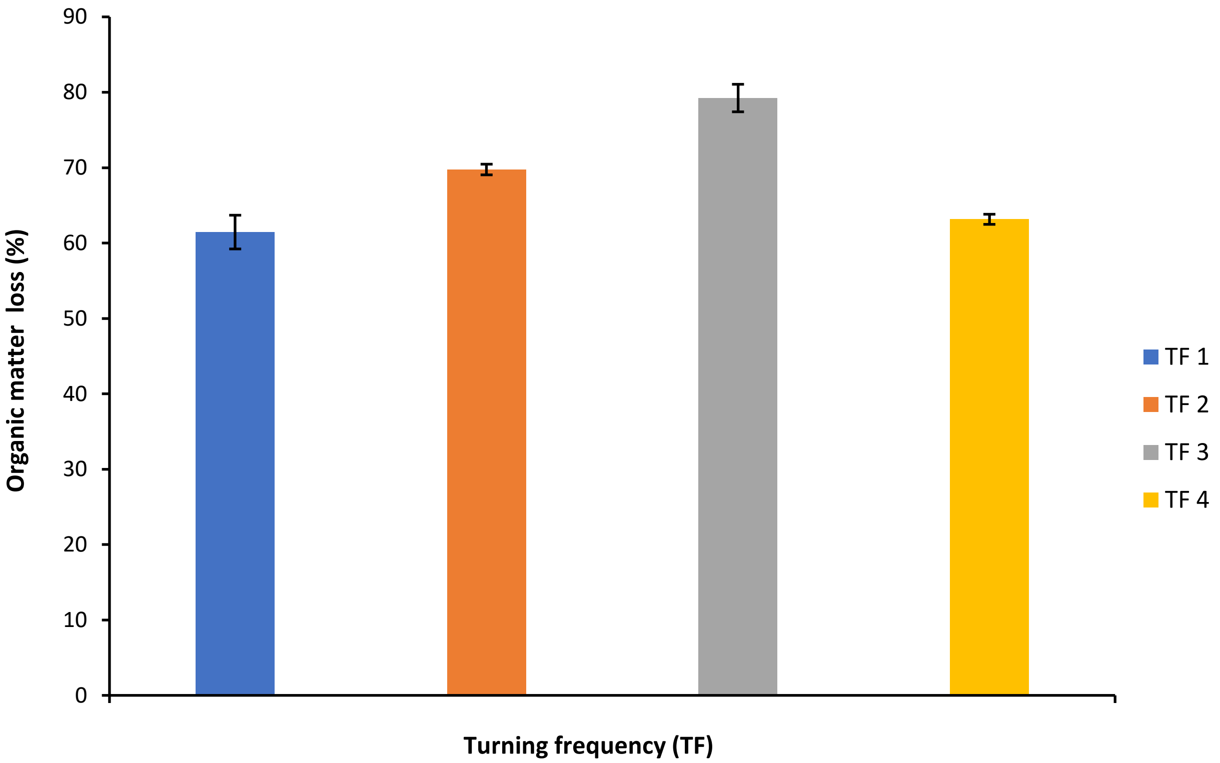

Figure 3. Organic matter loss for TF 1, TF 2, TF 3, and TF 4

Kinetics Modelling of Volatile Solid (VS) Degradation

A composting kinetics study of waste biodegradation is necessary to design the composting system. It is essential to determine waste biodegradability and develop a valuable measure for the loss of organic matter during composting (Hamoda et al., 1998). Proper modeling of substrate degradation progress is essential for predicting the composting process's operating variable (Qdais & Al-Widyan, 2016). Figure 4 shows the plot for VS changes over time with respect to each equation's order in the model for Mix B and Mix C. Based on the graph, the values for the rate of constant, k, and coefficient correlation (R^2) were determined. The values are presented in Table 2.

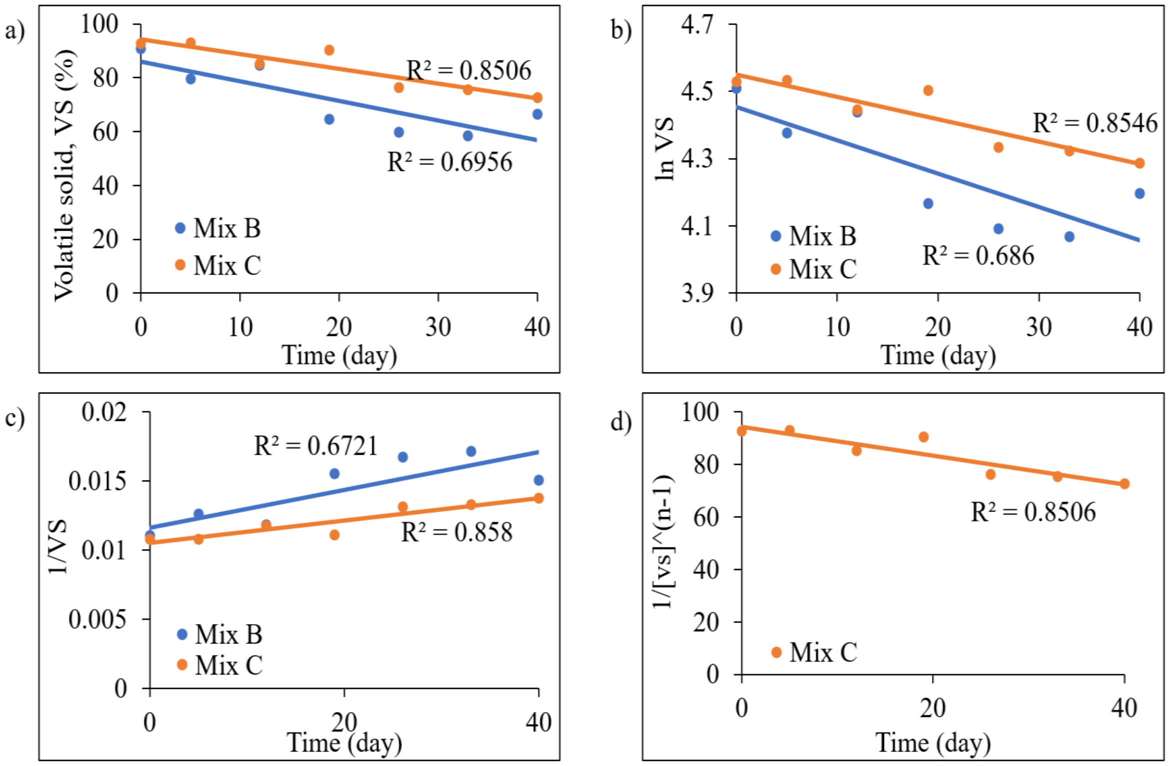

Figure 4. Principles of determining the mixing ratio k for (a) zero-, (b) first-, (c) second-, and (d) n-orders of Mix B and C treatment

The value of k in this study was slightly lower than in the previous study by Manu et al. (2016), where the range of k in first-order is 0.0045–0.0105. The reaction rate in Mix A was lower, possibly due to less microbial metabolism activity as the mixture has the lowest proportion of food waste. Meanwhile, the reaction rates for Mix B and Mix C were comparable with the previous study, which might be due to a similar proportion of feedstock mixture where Manu et al. (2016) used ~70% of food waste for the compost mixture. Overall, Mix B and Mix C showed a higher reaction rate, which means high degradation of organic matter. This is due to an optimum condition during composting compared to Mix A. This also supports the high OM loss observed in Mix B and Mix C, as shown previously.

A high value of EF and a low value of RMSE are chosen as the criteria for goodness of fit (Sangamithirai et al., 2015). At all kinetic models, Mix A did not adequately fit the experimental data because the R2 values obtained were very low (0.00002 – 0.0021). This might be due to the ratio in Mix A being unfavourable for composting. Similarly, Kabbashi et al. (2014) stated that poor performance was observed in closed systems with low R^2 compared to open systems. Meanwhile, for Mix B and C, the highest R^2 was obtained in zero-order (0.6956) and second-order (0.8580), respectively. A previous study by Jolanun et al. (2005) mentioned that an R^2 value of 0.67 is acceptable. The highest EF with the lower RMSE was found in second-order. For all of the derived models, second order models better predict the volatile solid dynamics of the composting process based on the R^2, EF, and RMSE. Similar observations have been reported by Ebrahimzadeh et al. (2017) where the second-order is the best kinetic model to predict the degradation of VS over time for all the reactors. The best model and mathematical equation of Mix B and C are shown in Table 4.

Table 2. The rate constant, coefficient correlation, modelling efficiency and root mean square error of Mix A, Mix B and Mix C by using zero-, first- and second-order equations

		Model number	k	R^2	EF	RMSE
Zero-order	Mix A	1	0.0277	0.0021	0.0021	8.1703
	Mix B	2	0.7290	0.6956	0.6956	6.5510
	Mix C	3	0.5477	0.8506	0.8506	3.1181
First-order	Mix A	4	0.0002	0.0006	0.0006	0.1089
	Mix B	5	0.0099	0.6860	0.6860	0.0911
	Mix C	6	0.0066	0.8546	0.8546	0.0371
Second-order	Mix A	7	0.0000005	0.00002	-0.0003	0.0015
	Mix B	8	0.0001	0.6721	0.5187	0.0016
	Mix C	9	0.00008	0.8580	0.8574	0.0004
n-order	Mix A	10	0.0141	0.0019	0.0018	4.4130
	Mix B	11	0.00000003	0.6285	0.6183	0.0000004
	Mix C	12	0.5477	0.8506	0.8506	3.118

Figure 5 shows the plot for VS changes over time with respect to each equation's order for TF 3. According to the results of a mathematical models discussed earlier, the values of the coefficients k, n, and statistical values R^2, RMSE, and EF are summarized in Table 3. It is observed that the correlation coefficient (R^2) for all experiments is higher than 0.67, showing a good linear regression fit for all models. Table 3 shows the correlation coefficients of four models. It was found that n-order models were better at predicting the VS profile for TF 3.

Table 3. The rate constant, coefficient correlation, modelling efficiency and root mean square error of TF 1, TF 2, TF 3 and TF 4 by using zero-, first- and second-order equations

		Model number	k	N	R^2	EF	RMSE
Zero-order	TF 1	1	0.209	0	0.9858	0.9857	0.35514
	TF 2	2	0.3535	0	0.8768	0.8767	1.87396
	TF 3	3	0.5257	0	0.9849	0.9842	1.050129
	TF 4	4	0.3131	0	0.9856	0.9856	0.593947
First-order	TF 1	5	0.0024	1	0.9883	0.9857	0.359728
	TF 2	6	0.0044	1	0.8903	0.8767	2.058163
	TF 3	7	0.0066	1	0.9925	0.9842	0.734076
	TF 4	8	0.0037	1	0.9891	0.9856	0.487071

Second-order	TF 1	9	0.00003	2	0.9903	0.9787	0.433917
	TF 2	10	0.00005	2	0.9013	0.8782	1.862446
	TF 3	11	0.00008	2	0.9973	0.9945	0.553396
	TF 4	12	0.00004	2	0.9918	0.9551	0.937975
n-order	TF 1	13	3.13E-05	1.9593	0.9902	0.9891	0.309581
	TF 2	14	6.87E-09	3.9095	0.9159	0.892447	1.750826
	TF 3	15	1.54E-08	2.9492	0.9988	0.998473	0.292891
	TF 4	16	2.38E-06	2.6818	0.9932	0.993123	0.367454

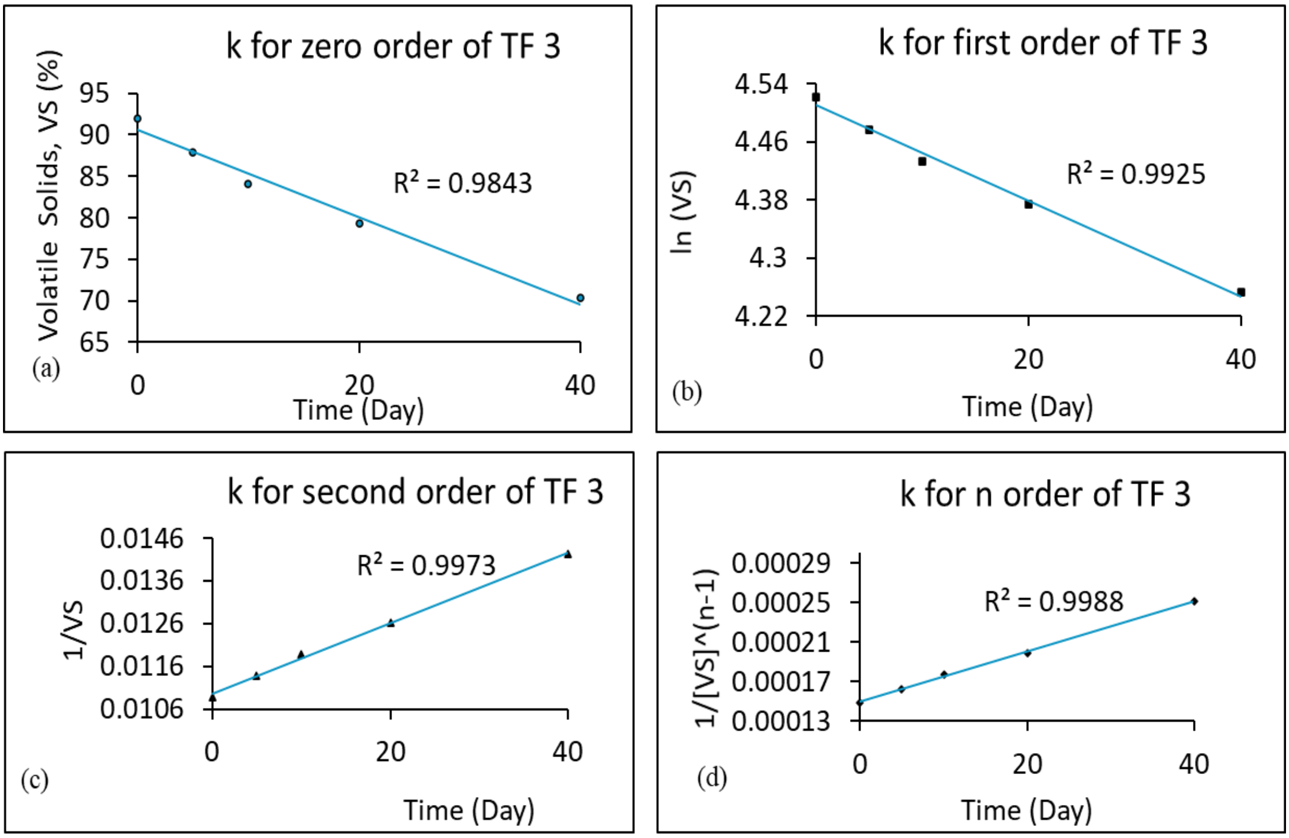

Figure 5. Principles of determining the rate constant k for (a) zero-, (b) first-, (c) second-, and (d) n-orders of TF 3 treatment.

After determining the VS rate constant k, mathematical equations were obtained to predict the degradation of compost VS over time. It should be noted that the kinetic study only focuses on the best mixture formulation and turning frequency, as shown in Figure 2 and Figure 3. Summarizing the data from Tables 2 and 3, the best model and mathematical equation for Mix B, Mix C, and 3-day TF (TF 3) are shown in **Table 4**. The specific equation was found by substituting the coefficient from the kinetic modelling with the one from the Table 1.

Table 4. The best model to predict changes in volatile solid over time for Mix B, Mix C, and TF 3

Treatment	Model number	Order	Specific equation
Mix B	8	2	$VS = \frac{88.6}{1 + 0.009t}$
Mix C	9	2	$VS = \frac{92.6}{1 + 0.007t}$
TF3	16	2.9492	$VS = \left(\frac{6692.08}{1 + 0.0169t}\right)^{0.5130}$

CONCLUSION

In this study, food waste: dry leaves mixture of 60:40 (Mix B) to 80:20 (Mix C) and TF every 3 days are recommended for achieving higher organic matter degradation. Application of the second-order model resulted in good responses for compost mixture Mix B and C. Meanwhile, the n-order model successfully estimated the VS changes for a 3-day TF.

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