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Modelling of Pilot-Scale Anaerobic Food Wastes Composting Process with Dry Leaves or Cow Manure

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ABSTRACT

Anaerobic composting is a promising method to fully transform food wastes into useful materials such as biofertilizer and biogas. In this study, the optimum proportions of food wastes containing vegetable, fruit and meat wastes with dry leaves or cow manure for composting were determined using the simplex centroid design and response optimizer. The effectiveness of the pilot-scale composting process was evaluated based on the targeted compost quality of C/N ratio at 21, pH value at 8 and electrical conductivity of 1 dS/m. Food wastes composting formulation with dry leaves suggested high percentage of dry leaves, 86.9% with low food wastes composition of 13.1% constituted by vegetable waste (1.1%), fruit waste (4.9%) and meat waste (7.1%). With cow manure formulation, only 6% of cow manure was recommended with another 94.0% of food wastes contributed by a fair mix of vegetable waste (23.2%), fruit waste (34.3%) and meat waste (36.5%). The developed regression models were experimentally validated with predicted responses obtained in acceptable ranges for C/N ratio (21.2 - 21.8), pH (7.92 - 7.99) and electrical conductivity (0.97 - 1.03 dS/m).

Keywords: Biofertilizer, biogas, mixture design, response surface optimization, simplex centroid design

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INTRODUCTION

Anaerobic composting consists of four main stages, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis in the absence of oxygen (Zhang et al., 2014). In the hydrolysis process, complex organic molecules are broken down into simple sugars, amino acids, and fatty acids. During the acidogenesis process, further breakdown of the remaining organic components by fermentative bacteria takes place producing short-chain fatty acids, carbon dioxide and hydrogen. Further digestion of simple molecules happens during the acetogenesis process where acetic acid, carbon dioxide and hydrogen are produced. The last stage, the methanogenesis is a biological process where intermediate products of the preceding processes are converted into methane, carbon dioxide and water, making the major components of biogas emitted from the system (Poulsen, 2013). The overall process can be described by the chemical reaction where organic material, e.g. glucose is biochemically digested into carbon dioxide (CO_2) and methane (CH_4) by anaerobic microorganisms.

Anaerobic composting of food waste is a biological process involving biodegradation of putrescible food waste into biofertilizer and by-product of biogas. It can be explained as a two-step process similar to the Bokashi composting (Power Knot, 2012). First, the beneficial microbes break down all food waste material including non-plant based through a fermentation process which creates an acidic environment that kills harmful pathogens in within and outside the system. The soil microbes then finish the decomposition. Unlike the aerobic composting which requires the help of heat for the soil microbes to break down plant materials at starting temperature of about 45°C and later the thermophilic phase at 50-70°C (Abdullah et al., 2013), the anaerobic composting happens at moderate temperatures below 45°C (mesophilic phase) and can degrade meat materials. The high biodegradability and moisture content of food waste are good characteristics for production of biofertilizer that can be used as nutrient source and soil conditioner (Girotto et al., 2015). In food waste handling, the anaerobic composting method is advantageous compared to the incineration method, owing to the high moisture content in food waste which often hinders the incineration process. Chen and colleagues (2008) found that food waste used in anaerobic composting has more potential for the biogas production than the municipal solid waste because food waste contains more than 80% organic content.

Food waste is discarded on daily basis due to routine activities of human living from domestic to agricultural and industrial. The composition of food waste is usually heterogeneous depending on the consumption habits of human, thus may affect the composting process. In optimizing the composting process, the proportion of composting materials need to be balanced or sometimes, other essential organic materials are added for functionality. In obtaining an optimized formulation, a systematic approach through statistical modelling via various design of experiment (DoE) is used to predict response variables and optimized factor variables of the processes. The DoE is relatively more efficient and cost-effective in developing and improving process models compared to the traditional trial and error method (Rao & Baral, 2011). As the inconsistency of food waste composition affects the quality of compost produced, this work aimed to find food waste formulation in terms of the vegetable, fruit and meat wastes proportions for an optimized anaerobic composting under the mesophilic phase at moderate temperatures. The dry leaves or cow manure were added into the anaerobic composting to improve the quality of compost.

The aim of using the pilot scale composter is that the composting process can be made in-situ, it saves transporting cost of waste to landfill or open space for aerobic compositing, preserves the appearance of the compost area, prevents bad odours and pests problems from open piles of aerobic composting area. The labour required to operate the composting process is also minimal as no turning pile or aeration mechanism is needed. It is also suitable for food waste which include meat waste to undergo anerobic composting as meat is strictly forbidden for aerobic composting. Despite its installation cost, the production of biogas can be a source of renewable energy. The anaerobic composting can be a mature and effective technology for food waste management system with low operating costs and high feasibility (Chang & Hsu, 2008; Girotto et al., 2015; Zhang et al., 2015). Recently, anaerobic food digestion approach and technology are getting more attention as recent researches have evaluated the feasibility of this system as an option for organic municipal waste management in populated urban areas like city Wildemanbuurt in Amsterdam (Goossensen, 2017) and city of Milan in Italy (Grosso et al., 2012).

MATERIALS AND METHODS

Substrates Preparation

This study consisted of two experimental parts for optimization of food wastes composting. The first experiment involved composting of food wastes and dry leaves, while the second experiment used food wastes and cow manure. The food wastes consisting vegetable, fruit and meat wastes were collected from Pasar Borong Selangor, Seri Kembangan. The dry leaves and cow manure were obtained from the Animal and Agricultural Unit of Universiti Putra Malaysia. These materials acted as bulking agents to improve the quality of compost by adjusting the moisture content and providing carbon and nitrogen sources for the compost produced.

Prior to anaerobic composting, foreign materials such as rubber band and plastic bags were discarded from the collected food wastes as they can impair microbial activities during composting process. All substrates were then shredded into fine substances with diameter less than 0.001 m using a food waste grinder (FWD 600 HS, Ecofast, Milano, Italy) before loading into the composter.

Pilot-scale Anaerobic Composter

The substrates were composted in a pilot-scale anaerobic composter (Cowtech CTM-100, CH Green Sdn. Bhd., Kuala Lumpur, Malaysia) located at Ladang 2, Universiti Putra Malaysia. Figure 1 shows the schematic diagram of the composter with dimensions of 1.8 m (height) × 1 m (width) × 4.5 m (length).

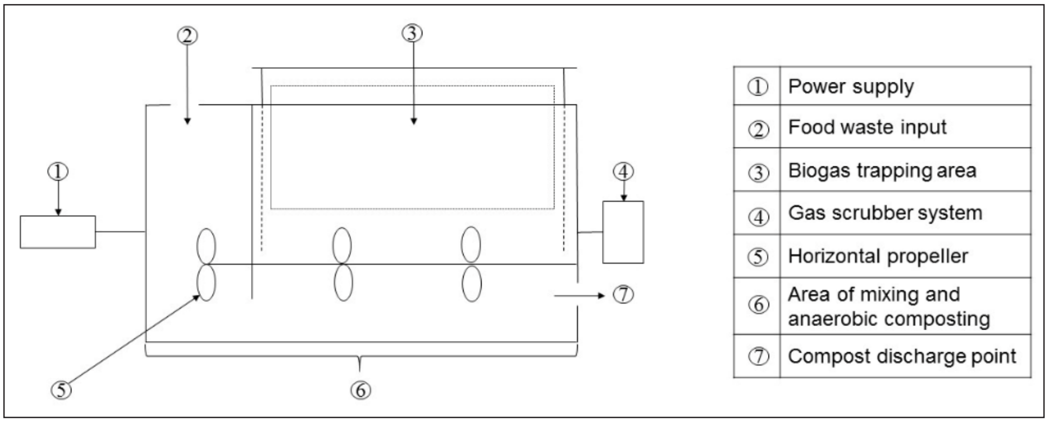

Figure 1. Schematic diagram of pilot-scale anaerobic composter

It is a hi-dry solid batch continuous composting system equipped with a power supply unit, feeding hopper, mixing and composting tank with 3000 kg volume, horizontal propeller, gas scrubber unit and discharge pump. The production capacity of biogas is approximately 2.76 - 5.52 kg/day. The start-up of the composting process was monitored for 30 days at 30 – 35°C with the first fill of 40 kg of effective microbe powder mixture in 40 kg of water. They effective microbe powder consists of microbes suitable for anaerobic composting, function well at lower temperature and acidic environment which included mainly yeasts, photosynthetic bacteria and lactic acid bacteria. They are meant to break down the food waste through fermentation process first and then the acidic environment created kills harmful pathogens, and lastly the soil microbes finish the decomposition. The temperature throughout the compositing process was dependent on the surrounding environmental temperature. The maximum substrates input of the composter was 100 kg/day but a daily input of 40 kg substrates was used in this study. The liquid compost was removed from the composter through a discharge pump and stored inside a pail. The amount of biogas produced was recorded daily before burning using a gas stove.

Mixture Experimental Design

Two types of mixtures, food wastes with dry leaves and food wastes with cow manure were used to evaluate the effects of substrates on the compost quality in terms of carbon to nitrogen (C/N) ratio, pH and electrical conductivity. These are the general physicochemical parameters widely used to examine the quality of compost produced (Bernal et la., 2009). The C/N ratio and moisture content of each substrate were determined to verify their capabilities as carbon source, nitrogen source and bulking agent.

The proportions for each substrate were generated following the simplex centroid design using Minitab 16 Statistical Software (Minitab Incorporation, Pennsylvania, USA). The simplex centroid design is capable in solving more complex experimental model as it contains higher order terms such as quadratic, full cubic, special cubic and special quartic models (Rao & Baral, 2011). This design is appropriate for the experimental design of this study with all components having the same range from 0 to 100 (Abdullah & Chin, 2010). A total of 23 runs were generated for food wastes with dry leaves experiment, and food wastes with cow manure experiment. The experiments were performed in random order to avoid bias sampling. The compost produced was collected after a minimum composting period of 30 days and analysed for physicochemical properties. The response parameters investigated were C/N ratio, pH and electrical conductivity.

Determination of Physicochemical Properties

The substrates and compost were analysed for various physicochemical properties including volatile solid content, total carbon content, total nitrogen content, C/N ratio, pH, electrical conductivity and moisture content. The volatile solid content and total carbon content were determined based on ash content (Larney et al., 2003). The ash content was assessed following Abdullah and Chin (2010), and Mohee and co-workers (2008). About 2.5 g of sample was placed in clean crucible in a muffle furnace at 550°C for 2 hours. The ash content is defined by the difference of sample weight before and after placing in the furnace. The percentage of ash content was calculated using Eq. 1.

$$\% \text{ Ash} = \frac{\text{Weight}_{\text{Before}} - \text{Weight}_{\text{After}}}{\text{Weight}_{\text{Before}}} \times 100\% \tag{1}$$

The volatile solid of sample was then calculated using Eq. 2 (Abdullah & Chin, 2010), followed by total carbon content using Eq. 3 (Larney et al., 2003).

$$\% \text{ Volatile solid} = 100\% - \% \text{ Ash} \tag{2}$$

$$\% \text{ Total organic carbon} = \frac{\% \text{ Volatile solid}}{1.8} \tag{3}$$

The nitrogen content was determined by Kjeldahl method (Unmar & Mohee, 2008). The sample of 0.15 g was inserted into a boiling tube with 0.8 g of mixed catalyst and 2.5 mL of concentrated sulphuric acid were added. The boiling tube was heated slowly on a heating coil to break all the bonds in the sample. The digestion process was completed when the solution became clear greenish blue. After cooling, the sample was added with

10 mL of distilled water and transferred into distillation tube. Prior to distillation process, 10 mL of 45% sodium hydroxide solution was slowly added to separate the solution into two layers. A conical flask containing 10 mL of 2% boric acid and three drops of indicator was used to collect the distillate. After distillation process of 120 seconds, the conical flask with distillate and boric acid was titrated using 0.05 N of sulphuric acid until light pink persist. A similar procedure was performed for the blank sample. The percentage of nitrogen content was calculated following Eq. 4 (Codell & Verderame, 1954).

$$\% \text{ Total nitrogen} = \frac{(R-S)\text{ x } 1.4007 \text{ x } N}{W} \text{ x } 100\% \tag{4}$$

where *R* is volume of sulphuric acid to titrate boric acid (mL), *S* is volume of sulphuric acid to titrate blank (mL), *N* is normality of sulphuric acid of 0.05 N, and *W* is sample weight (g).

The C/N ratio refers to total organic carbon content to total nitrogen content of the sample as shown in Eq. 5.

$$\text{C/N ratio} = \frac{\text{Total organic carbon}}{\text{Total nitrogen}} \text{ x } 100\% \tag{5}$$

The pH value was measured using a handheld pH meter (Mi806, Milwaukee Instruments Inc., North Carolina, USA) (Kumar et al., 2010). The sample was diluted with deionized water in a weight ratio of 1:10, and stirred for 1 hour at 150 rpm in a shaking water bath (BS-21, Jeio Tech Co. Ltd., Korea). The mixture was left standing to reach dormant state followed by measuring the pH of the top layer or supernatant.

The electrical conductivity was determined following Lin (2008) and Chen et al. (2008). The sample of 5 g was diluted with 25 mL of deionized water and mixed for 30 minutes at room temperature until a homogenous state is reached prior to filtration using Whatman No.1 filter paper. The electrical conductivity of the filtrate was measured using a portable electrical conductivity meter (Mi806, Milwaukee Instruments Inc., North Carolina, USA).

The moisture content was determined by conventional oven method as described by Kumar et al. (2010). About 200 g of sample was dried in an oven at 105°C for 24 hours until constant weight is obtained. The moisture content is defined as the weight loss of sample. The percentage of moisture content was calculated following Eq. 6 (Schwab et al., 1994).

$$\% \text{ Moisture} = \frac{M_W - M_S}{M_W} \text{ x } 100\% \tag{6}$$

where M_W is weight of food wastes compost (kg) and M_S is the weight of dry solids of food wastes compost (kg). The response variables values are reported as the average of triplicate measurements to ensure its repeatability.

RESULTS AND DISCUSSION

Characteristics of Substrates for Anaerobic Composting

The substrates used for anaerobic composting in this study were characterised for carbon content, nitrogen content, C/N ratio, pH and moisture content as summarised in Table 1. The meat waste and cow manure contained relatively high nitrogen contents of 5.87% and 3.96%, respectively implying that both meat waste and cow manure could be good nitrogen sources. The meat waste showed the lowest C/N ratio while dry leaves had the highest C/N ratio. The moisture level in fruit waste is the highest (81.34%) followed by meat waste, vegetable waste, cow manure and dry leaves has the least (3.48%). These indicate that dry leaves possess good absorption capacity and is suitable as bulking agent for adjusting the moisture of food wastes in order to achieve better composting process.

Table 1
Physicochemical properties of substrates used

Properties	Vegetable waste	Fruit waste	Meat waste	Dry leaves	Cow manure
Carbon content (%)	38.79 ± 2.13	42.29 ± 1.14	39.87±1.14	46.4 ± 2.27	34.88 ± 1.91
Nitrogen content (%)	2.45 ± 0.04	1.21 ± 0.06	5.87 ± 0.06	0.24 ± 0.04	3.96 ± 0.10
C/N ratio	16.86	39.90	6.79	193.33	8.81
pH	6.35 ± 0.01	5.50 ± 0.01	5.78 ± 0.01	6.61 ± 0.02	9.21 ± 0.01
Moisture content (%)	74.78 ± 0.93	81.34 ± 0.93	75.19 ± 1.36	3.48 ± 0.50	72.23 ± 2.80

Food Wastes with Dry Leaves Composting

Modelling of Composting Process. Table 2 presents the effects of food wastes with dry leaves composting on the quality of compost such as C/N ratio, pH and electrical conductivity including the biogas amount. Several regression models were fitted into the data obtained including linear, quadratic, special cubic, full cubic, and special quartic models.

The criteria in selecting the best fitted model to the data are low standard deviation, low predicted sum of squares (PRESS), and high predicted R-squared (R^2_{pred}) (Cornell, 2002). Based on the selection criteria for best model, it was found that special cubic model, linear model, and quadratic model were the best fitted models for C/N ratio ($R^2_{pred\,=}\,0.873$), pH value ($R^2_{pred\,=}\,0.772$) and electrical conductivity ($R^2_{pred} = 0.798$), respectively (Table 3).

The regression coefficients of the three responses of food wastes with dry leaves composting are shown in Table 4.

All of the models fitted the experimental data well as indicated by the high coefficients of determination ranging from 0.835 to 0.997. The best fitted mathematical models for C/N ratio, pH, and electrical conductivity are given in Eq. 7 - Eq. 9.

Table 2
Mixture experimental design of food wastes with dry leaves composting

Run	Independent variables				Response variables			
	Vegetable waste, x_1 (%)	Fruit waste, x_2 (%)	Meat waste, x_3 (%)	Dry leaves, x_4 (%)	C/N ratio, Y_{CN}	pH, Y_{pH}	Electrical conductivity, Y_{EC}	Biogas amount (m^3)
1	25	25	25	25	36.32	7.81	0.915	3.60
2	50	50	0	0	49.92	7.77	0.679	3.45
3	62.50	12.50	12.50	12.50	30.76	7.85	0.836	3.75
4	0	50	0	50	37.25	7.88	0.913	3.75
5	33.33	0.00	33.33	33.33	27.86	7.90	0.937	3.50
6	33.33	33.33	0.00	33.33	32.78	7.82	0.857	3.45
7	50	0	50	0	26.73	8.04	0.756	3.75
8	33.33	33.33	33.33	0	21.25	7.85	0.808	3.70
9	12.50	12.50	12.50	62.50	23.34	7.95	1.005	3.60
10	0	0	100	0	46.60	8.24	1.216	3.85
11	50	0	0	50	24.11	7.97	0.944	3.65
12	0	0	50	50	29.92	8.01	0.953	3.75
13	0	33.33	33.33	33.33	31.72	7.90	0.867	0.95
14	0	100	0	0	182.00	7.77	0.581	0.80
15	12.50	12.50	62.50	12.50	29.19	7.98	0.979	1.10
16	100	0	0	0	43.12	7.65	0.706	1.20
17	12.50	62.50	12.50	12.50	63.73	7.85	0.644	0.75
18	0	0	0	100	24.27	8.01	1.065	0.95
19	0	50	50	0	33.20	8.06	0.765	0.70
20	100	0	0	0	42.73	7.72	0.713	0.85
21	0	100	0	0	186.40	7.81	0.586	0.90
22	0	0	100	0	43.67	8.23	1.254	1.00
23	0	0	0	100	26.85	8.05	1.076	2.70

Table 3
Model summary statistics for response variables of food wastes with dry leaves composting

Source	Standard deviation	Regression, R^2 (%)	Predicted regression, R^2_{pred} (%)	Adjusted regression, R^2_{adj} (%)	Predicted sum of square, PRESS
C/N ratio					
Linear	28.34	64.63	41.33	59.04	25308
Quadratic	6.56	98.70	92.92	97.81	30555
Special cubic	3.56	99.73	87.31	99.35	5475
Full cubic	3.22	99.86	42.25	99.47	24914
Special quartic	4.62	99.70	43.09	98.91	24552
pH					
Linear	0.065	83.48	77.18	80.87	0.110
Quadratic	0.051	92.97	56.85	88.10	0.208
Special cubic	0.034	97.82	50.72	94.66	0.237
Full cubic	0.033	98.67	47.16	95.14	0.255
Special quartic	0.033	98.66	0.00	95.07	3.384
Electrical conductivity					
Linear	0.077	84.56	77.19	82.13	0.167
Quadratic	0.048	95.85	79.80	92.98	0.148
Special cubic	0.038	98.25	25.21	95.72	0.547
Full cubic	0.015	99.81	60.79	99.30	0.287
Special quartic	0.020	99.68	0.00	98.84	0.943

Table 4
Regression coefficients for response variables of food wastes with dry leaves composting

Term	C/N ratio	pH	Electrical conductivity
b_1	43.3	7.72	0.707
b_2	183.5	7.78	0.567
b_3	45.5	8.19	1.230
b_4	25.6	7.99	1.070
b_{12}	-258.1*	-	0.246
b_{13}	-69.9*	-	-0.560
b_{14}	-42.2*	-	0.361
b_{23}	-329.5*	-	-0.432*
b_{24}	-275.1*	-	0.329
b_{34}	-23.5*	-	-0.625*
b_{123}	146.5*	-	-
b_{124}	375.3	-	-
b_{134}	210.9	-	-
b_{234}	483.8	-	-
R^2	0.997	0.835	0.959

Note. Subscripts: 1 = vegetable waste; 2 = fruit waste; 3 = meat waste; 4 = dry leaves.
* indicates significant effect at $P < 0.05$.

$$Y_{\mathrm{CN}} = 43.3x_1 + 183.5x_2 + 45.5x_3 + 25.6x_4 - 258.1x_1x_2 - 69.9x_1x_3 - 42.2x_1x_4 - 329.5x_2x_3 - 275.1x_2x_4 - 23.5x_3x_4 + 146.5x_1x_2x_3 + 375.3x_1x_2x_4 + 210.9x_1x_3x_4 + 483.8x_2x_3x_4 \quad (7)$$

$$Y_{\mathrm{pH}} = 7.72x_1 + 7.78x_2 + 8.19x_3 + 7.99x_4 \quad (8)$$

$$Y_{\mathrm{EC}} = 0.707x_1 + 0.567x_2 + 1.230x_3 + 1.070x_4 + 0.246x_1x_2 - 0.560x_1x_3 + 0.361x_1x_4 - 0.432x_2x_3 + 0.329x_2x_4 - 0.625x_3x_4 \quad (9)$$

A positive interaction coefficient indicates a synergistic effect while a negative term denotes an antagonistic effect of the parameters on the response value (Abdullah & Chin, 2010). The linear coefficients of b_1, b_2, b_3 and b_4 denote that vegetable waste, fruit waste, meat waste, and dry leaves have synergistic effects on C/N ratio (Table 4). For the quadratic interaction coefficients, all of the substrates have significant antagonistic effects ($P < 0.05$) for the reduction of C/N ratio which is desirable. Moreover, the coefficients b_{23} and b_{34} imply that reduction of fruit waste and meat waste, and meat waste and dry leaves significantly ($P < 0.05$) increased the electrical conductivity of the compost. These results recommend the blending of two substrates in producing the best quality compost for food wastes with dry leaves anaerobic composting.

Contour Plots and Response Surface Plots. Figures 2(a) - (c) illustrate the contour plots and 3D surface plots of the three responses, C/N ratio, pH and electrical conductivity of food wastes with dry leaves composting. Figure 2(a) shows that increasing dry leaves reduced the C/N ratio and produced a better quality of compost. The compost with good C/N ratio ranging from 10 to 25 (Aparma et al., 2008) can be met when the mixture contained moderate amount of vegetable and meat wastes as well as minute amount of fruit waste with abundance of dry leaves. The level of pH increased with meat waste and dry leaves but decreased with vegetable and fruit wastes as shown in Figure 2(b). The pH of each substrate is affected by its individual physicochemical properties (Table 1) and also its percentage used in the mixture experimental design. Figure 2(c) shows that almost all combination of food wastes with dry leaves composting produced electrical conductivity of less than 1.0. This reveals that compost generated from food wastes with dry leaves could be used to a certain extent as the direct substitution for soil (US Composting Council, 1990). Higher electrical conductivity can be achieved using larger amount of meat waste and dry leaves.

The overlaid contour plots of all responses, C/N ratio, pH and electrical conductivity for food wastes with dry leaves composting are shown in Figure 3. It is observed that good quality organic compost can be achieved using any combination of vegetable, fruit and meat wastes with dry leaves that fall within the white zone, also known as the feasible region.

These results suggest using a combination of higher amount of dry leaves, lesser fruit and meat wastes, and little vegetable waste to obtain good quality of compost.

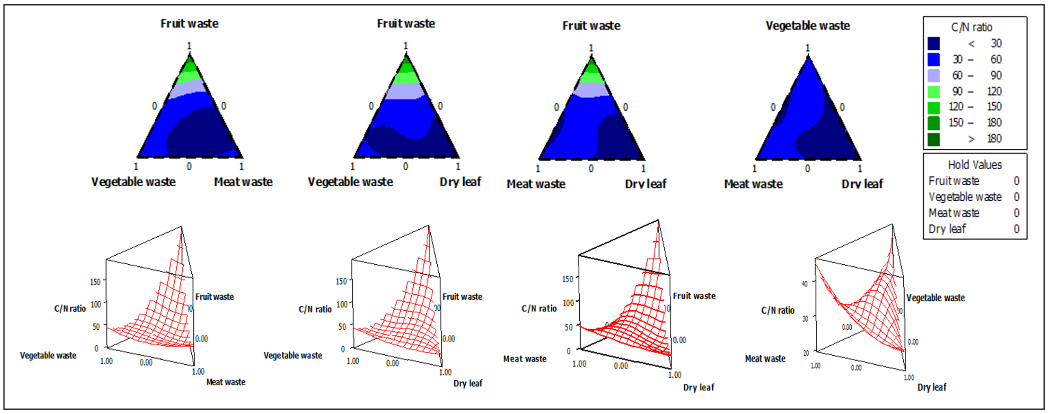

Figure 2(a). Mixture contour plots and 3D surface plots of C/N ratio of food wastes with dry leaves composting

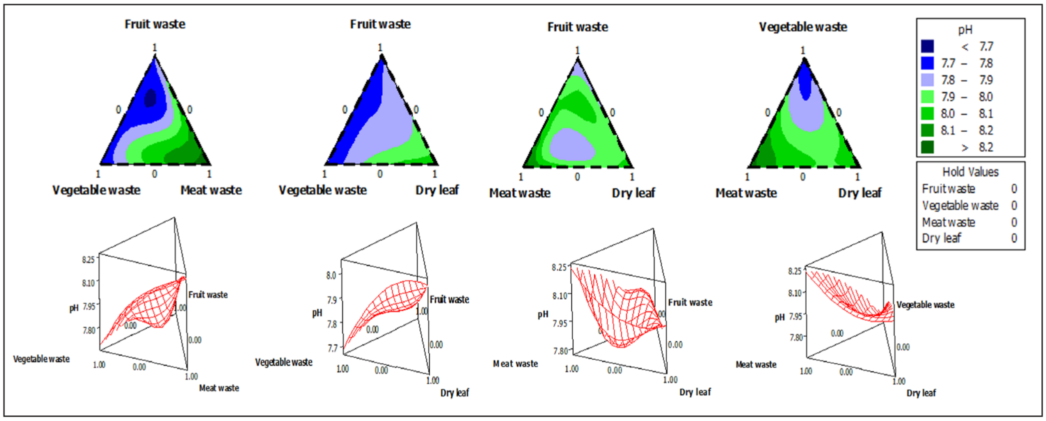

Figure 2(b). Mixture contour plots and 3D surface plots of pH of food wastes with dry leaves composting

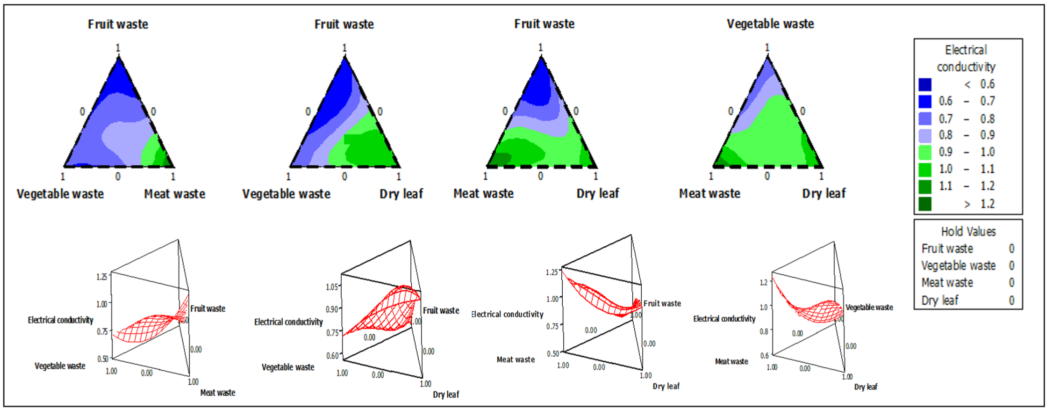

Figure 2(c). Mixture contour plots and 3D surface plots of electrical conductivity of food wastes with dry leaves composting

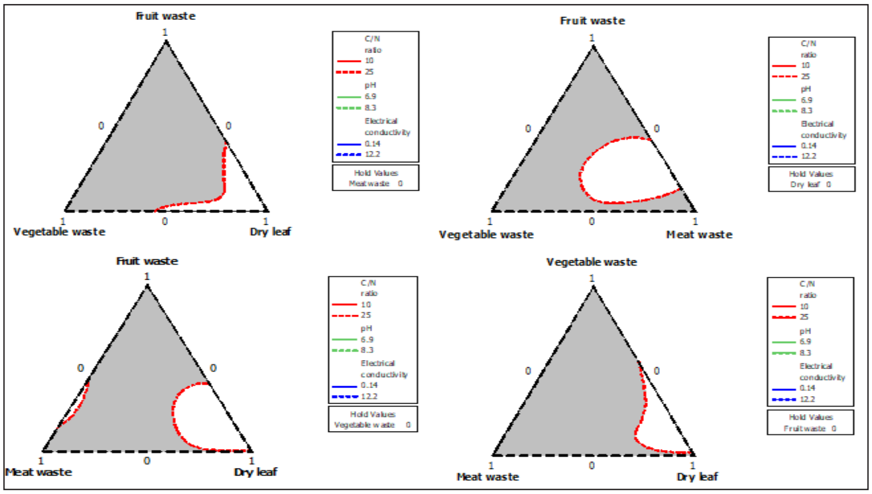

Figure 3. Overlaid contour plots of C/N ratio, pH and electrical conductivity of food wastes with dry leaves composting

Response Optimization and Model Validation. Response optimization allows simultaneous identification of variable settings that jointly optimizze a set of responses and illustrates in optimization plot. The joint optimization must fulfil the requirements of all responses and measured by the composite desirability. Figure 4 shows the optimization plot of food wastes with dry leaves composting. The optimum proportion for food wastes with dry leaves composting was 1.16% vegetable waste, 4.89% fruit waste, 7.07% meat waste, and 86.88% dry leaves with the composite desirability of 0.998. These imply that the all the target values for responses were achieved. The range of individual desirability (0.997 - 0.998) reveals that the model developed is equally effective at minimising C/N ratio, maximising pH value, and electrical conductivity. The desirable responses attained are 20.98 for C/N ratio, 7.99 for pH, and 1.02 dS/m for electrical conductivity.

An increase in vegetable and fruit wastes increases the C/N ratio and reduces the electrical conductivity and pH value which is not favourable for the compost quality (Figure 4). The goal is to minimise C/N ratio, maximise pH value, and maximise electrical conductivity. Therefore, the optimal settings of both vegetable and fruit wastes are at the minimum levels in the experiment. An increase in meat waste and dry leaves increases the three responses as the electrical conductivity and pH were greater than the C/N ratio. In order to compromise between the contradictory goals, the optimal settings of vegetable, fruit and meat wastes with dry leaves are in the intermediate range of 1.16%, 4.89%, 7.07% and 86.88%, respectively. The possible usage of high percentage of dry leaves at 86.88% could be related to its antagonistic effects of higher pH values 6.61 to raise the alkalinity of food waste pH averaging at 5.88 and relatively lower moisture content of 3.48% to balance the electrical conductivity to 1 dS/m.

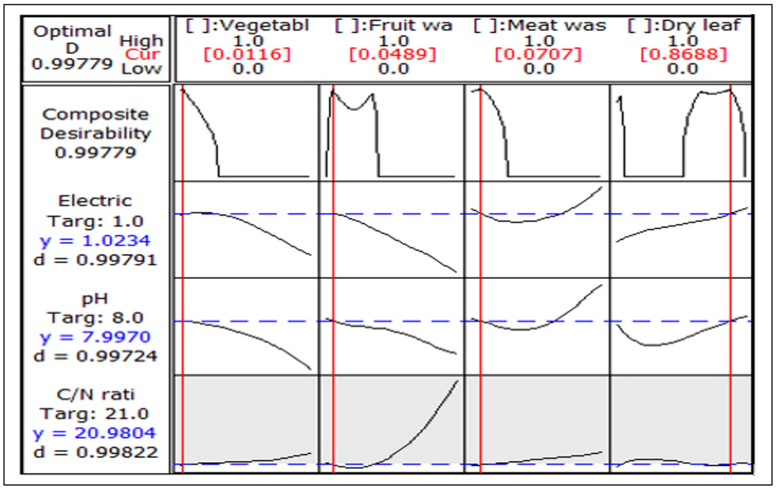

Figure 4. Optimization plot of food wastes with dry leaves composting

The optimum proportion of food wastes with dry leaves obtained was used for validating the models. The predicted responses obtained were C/N ratio of 21.83, pH value of 7.99, and electrical conductivity of 1.03 dS/m, which are very close to the target values from the responses of 21.0, 8.0 and 1.0, respectively. These results are in agreement with Aparma et al. (2008) who reported the C/N ratio of compost ranging from 10 to 25, Shyamala and Belagali (2012) on pH range between 6.9 and 8.3, and US Composting Council (1990) on electrical conductivity of 0.14 - 12.2 dS/m.

Food Wastes with Cow Manure Composting

Modelling of Composting Process. The effects of food wastes with cow manure composting on the compost quality based on C/N ratio, pH, electrical conductivity, and the biogas content are shown in Table 5.

The responses data were fitted into several regression models such as linear, quadratic, special cubic, full cubic and special quartic. Following the model selection criteria of low standard deviation, low R^2_{pred} and high PRESS, it is observed that special quartic model best fitted to C/N ratio with $R^2_{pred} = 0.933$, quadratic model to pH value with $R^2_{pred} = 0.623$, and full cubic model to electrical conductivity with $R^2_{pred} = 0.820$ (Table 6).

Generally, a model is considered a valid model by having the R^2 value greater than 0.6 (Gong et al., 2007). Table 7 presents the regression coefficients for the three responses of food wastes with cow manure composting.

The high coefficients of determination ranging between 0.876 and 0.998 indicate that all of the models fit the experimental data well. The best fitted regression models for C/N ratio, pH, and electrical conductivity are presented in Eq. 10 - Eq. 12.

Table 5
Mixture experimental design of food wastes with cow manure composting

Run	Independent variables				Response variables			
	Vegetable waste, x_1 (%)	Fruit waste, x_2 (%)	Meat waste, x_3 (%)	Cow manure, x_4 (%)	C/N ratio, Y_{CN}	pH, Y_{pH}	Electrical conductivity, Y_{EC}	Biogas amount (m^3)
1	50	0	50	0	25.67	8.02	0.812	4.10
2	33.33	33.33	0.00	33.33	37.68	7.78	1.271	3.75
3	0	0	50	50	30.45	7.94	1.284	3.85
4	0	0	0	100	28.73	8.09	1.313	3.75
5	62.50	12.50	12.50	12.50	32.14	7.95	1.178	3.80
6	0	100	0	0	185.00	7.75	0.584	3.90
7	12.50	62.50	12.50	12.50	63.96	7.91	0.957	3.80
8	33.33	0.00	33.33	33.33	33.33	7.88	1.357	3.40
9	50	0	0	50	41.42	7.85	1.379	3.90
10	12.50	12.50	62.50	12.50	33.72	7.97	1.256	3.65
11	100	0	0	0	43.00	7.67	0.704	3.94
12	0	50	50	0	32.89	8.03	0.767	3.60
13	0	50	0	50	34.18	7.92	1.149	0.80
14	33.33	33.33	33.33	0.00	22.45	7.87	0.802	1.00
15	25	25	25	25	34.71	7.84	1.280	1.00
16	50	50	0	0	49.98	7.77	0.651	1.10
17	0	0	100	0	45.78	8.21	1.212	0.90
18	0.00	33.33	33.33	33.33	30.80	7.83	1.190	0.85
19	12.50	12.50	12.50	62.50	31.08	8.02	1.292	0.75
20	100	0	0	0	40.73	7.81	0.578	0.85
21	0	100	0	0	184.40	7.74	0.721	0.94
22	0	0	100	0	44.53	8.24	1.253	0.98
23	0	0	0	100	25.85	8.04	1.470	2.80

Table 6
Model summary statistics for three responses of food wastes with cow manure composting

Source	Standard deviation	Regression, R^2 (%)	Predicted regression, R^2_{pred} (%)	Adjusted regression, R^2_{adj} (%)	Predicted sum of square, PRESS
C/N ratio					
Linear	28.92	62.19	38.11	56.22	26001
Quadratic	6.12	98.84	93.13	98.04	2888
Special cubic	3.46	99.74	89.62	99.37	4361
Full cubic	2.20	99.94	92.70	99.79	3068
Special quartic	3.33	99.84	93.26	99.42	2833
pH					
Linear	0.080	73.03	61.73	68.77	0.175
Quadratic	0.066	87.63	62.26	79.06	0.171
Special cubic	0.072	89.66	0.00	74.72	0.984
Full cubic	0.074	92.78	0.00	73.52	1.770
Special quartic	0.073	93.00	0.00	74.34	25.384
Electrical conductivity					
Linear	0.163	72.58	60.48	68.56	0.731
Quadratic	0.112	91.22	54.71	85.16	0.837
Special cubic	0.098	95.31	0.00	88.54	2.506
Full cubic	0.076	98.11	81.99	93.08	0.333
Special quartic	0.084	97.72	0.00	91.63	3.730

$$Y_{\mathrm{CN}} = 42x_1 + 185x_2 + 45x_3 + 27x_4 - 253x_1x_2 - 71x_1x_3 + 27x_1x_4 - 328x_2x_3 - 287x_2x_4 - 23x_3x_4 + 2550{x_1}^2x_2x_3 - 413{x_1}^2x_2x_4 - 1605{x_1}^2x_3x_4 + 1506{x_2}^2x_3x_4 - 1986x_1{x_2}^2x_3 + 2027x_1{x_3}^2x_4 + 1437x_1x_2{x_4}^2 \tag{10}$$

$$Y_{\mathrm{pH}} = 7.75x_1 + 7.75x_2 + 8.22x_3 + 8.08x_4 + 0.12x_1x_2 + 0.06x_1x_3 - 0.120x_1x_4 - 0.04x_2x_3 + 0.02x_2x_4 - 0.96x_3x_4 \tag{11}$$

$$Y_{\mathrm{EC}} = 0.643x_1 + 0.655x_2 + 1.235x_3 + 1.394x_4 + 0.013x_1x_2 - 0.503x_1x_3 + 1.447x_1x_4 - 0.706x_2x_3 + 0.504x_2x_4 - 0.116x_3x_4 + 2.981x_1x_2x_3 + 4.733x_1x_2x_4 + 5.243x_1x_3x_4 + 4.068x_2x_3x_4 \tag{12}$$

Table 7 shows positive magnitudes in all of the linear coefficients (b_1, b_2, b_3 and b_4) implying that vegetable waste, fruit waste, meat waste and cow manure have synergistic effect on C/N ratio. In quadratic terms, vegetable waste with fruit waste (b_{12}) or meat waste (b_{13}), and fruit waste with meat waste (b_{23}) or cow manure (b_{24}) show significant antagonistic effect ($P < 0.05$) on the C/N ratio of compost. In addition, the coefficient b_{34} denotes that

Table 7
Regression coefficients for response variables of food wastes with cow manure composting

Term	C/N ratio	pH	Electrical conductivity
b_1	42	7.75	0.643
b_2	185	7.75	0.655
b_3	45	8.22	1.235
b_4	27	8.08	1.394
b_{12}	-253*	0.12	0.013
b_{13}	-71*	0.06	-0.503
b_{14}	27	-0.12	1.447*
b_{23}	-328*	-0.04	-0.706
b_{24}	-287*	0.02	0.504
b_{34}	-23	-0.96*	-0.116
b_{123}	-	-	2.981
b_{124}	-	-	4.733
b_{134}	-	-	5.243
b_{234}	-	-	4.068
b_{1123}	2550*	-	-
b_{1124}	-413	-	-
b_{1134}	-1605	-	-
b_{2234}	1506*	-	-
b_{1223}	-1986*	-	-
b_{1334}	2027*	-	-
b_{1244}	1437	-	-
R^2	0.998	0.876	0.981

Note. Subscripts: 1 = vegetable waste; 2 = fruit waste; 3 = meat waste; 4 = cow manure.
* indicates significant effect at $P < 0.05$.

the two-blend mixture of meat waste and cow manure significantly ($P < 0.05$) contributes to the reduction of pH value. The significant coefficient of b_{14} indicates that vegetable waste and cow manure have a significant effect on electrical conductivity of compost. It is suggested that by using two-blend mixture of vegetable waste and cow manure would produce a better quality of compost in terms of electrical conductivity.

Contour Plots and Response Surface Plot. The contour plots and 3D surface plots of all the responses, C/N ratio, pH and electrical conductivity of food wastes with cow manure composting are shown in Figure 5(a) - (c). Figure 5(a) illustrates that higher amount of cow manure produced compost with lower C/N ratio which is of better quality. It can be deduced that the mixture consisting moderate amount of vegetable and meat wastes, and little fruit waste with larger amount of cow manure for composting is suitable to generate good quality compost having the desired C/N ratio. The pH level increased with meat waste and cow manure but decreased with vegetable and fruit wastes as shown in Figure 5(b). An excessive amount of cow manure in composting contributes to a very high pH value of compost which is unfavourable for the use of plantation. Figure 5(c) illustrates that the increase in vegetable and fruit wastes reduces the electrical conductivity of compost to less than 1 dS/m. It is suggested that the compost produced from mixture of large vegetable and fruit wastes with little cow manure could be used for soil substitution (US Composting Council, 1990). An increase in cow manure also increases the electrical conductivity of the compost generated which is highly desirable.

Figure 6 presents the overlaid contour plots of the three responses including C/N ratio, pH, and electrical conductivity for food wastes with cow manure composting. Any combination of vegetable, fruit, and meat wastes with cow manure that falls into the white zone also known as feasible region, is consider suitable for composting in producing good quality compost. The suggested combination of substrates for food wastes with cow manure composting is moderate amount of vegetable, fruit, and meat wastes with little cow manure.

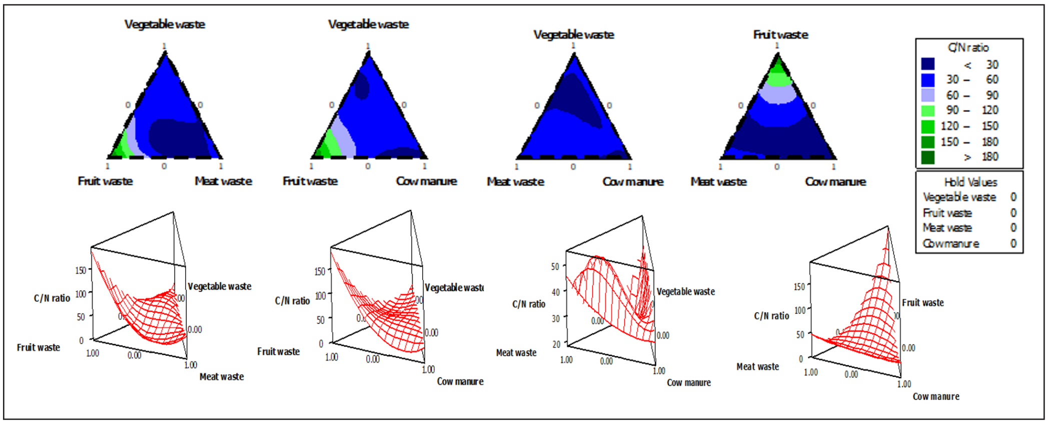

Figure 5(a). Mixture contour plots and 3D surface plots of C/N ratio of food wastes with cow manure composting

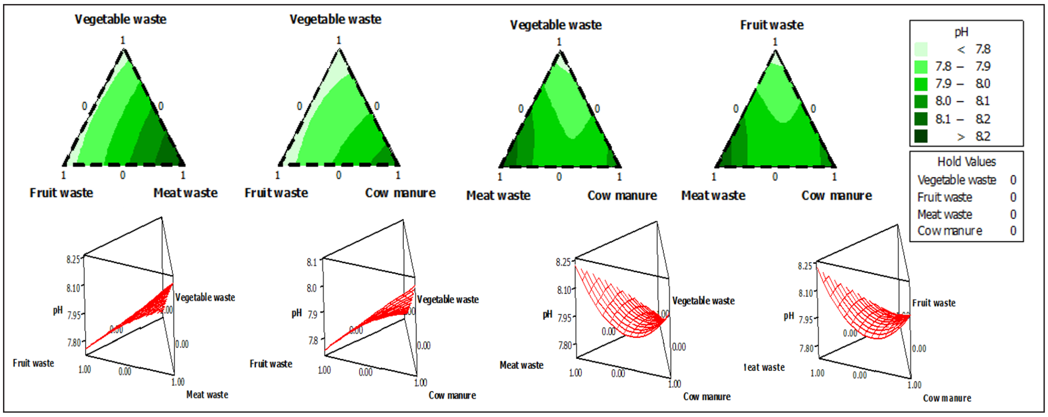

Figure 5(b). Mixture contour plots and 3D surface plots of pH of food wastes with cow manure composting

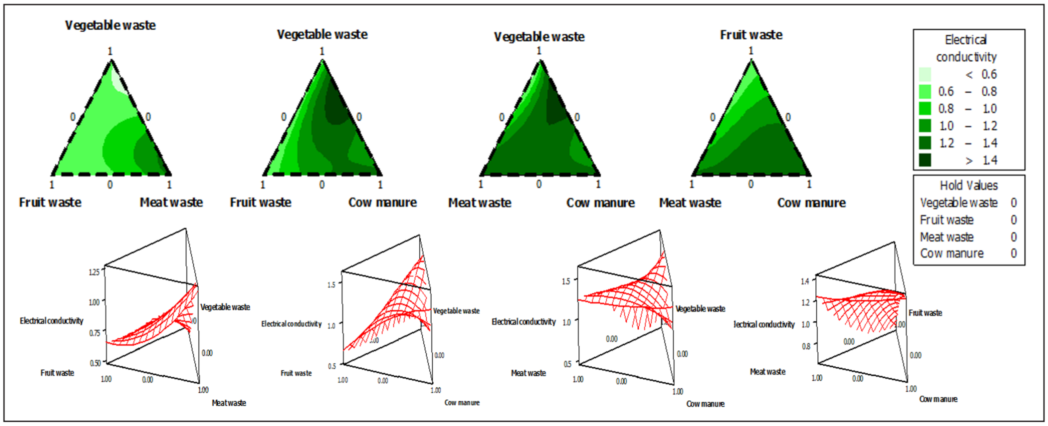

Figure 5(c). Mixture contour plots and 3D surface plots of electrical conductivity of food wastes with cow manure composting

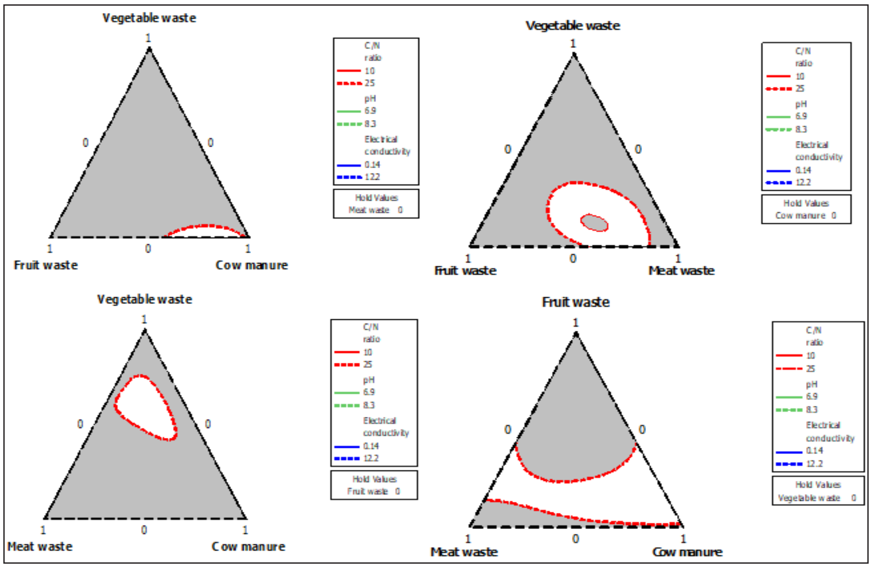

Figure 6. Overlaid contour plots of C/N ratio, pH and electrical conductivity of food wastes with cow manure composting

Response Optimization and Model Validation. The optimization plot of food wastes with cow manure composting is illustrated in Figure 7. The optimum settings for food wastes with dry leaves composting were 23.18% vegetable waste, 34.34% fruit waste, 36.46% meat waste, and 6.01% cow manure, with composite desirability of 0.977. The composite desirability is close to unity, indicating that the settings have achieved favourable results for all responses. The individual desirability shows that the settings are effective at maximising electrical conductivity (0.999) followed by minimising C/N ratio (0.997) and maximising pH value (0.937). The favourable responses obtained for C/N ratio, pH and electrical conductivity were 21.01, 7.93, and 1.0 dS/m, respectively. The recommended percentage of cow manure at 6.01% is relatively lower than the earlier section using dry leaves at 86.88% because of its antagonistic effect. Cow manure has high pH values of 8.81 and high moisture content of 72.23% which are not required for targeted pH=8 and electrical conductivity of 1.0 dS/m. The suggested usage percentage of dry leaves or cow manure is based on the balancing of the pH and electrical conductivity for a conducive environment for microbial activity with main substrates composition comprising of vegetable, fruit and meat wastes.

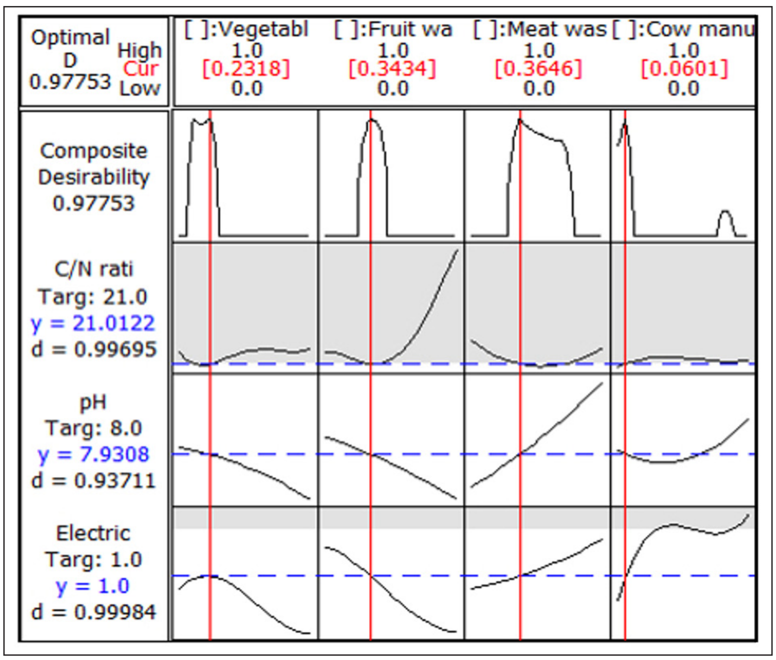

Figure 7. Optimization plot of food wastes with cow manure composting

Figure 7 shows that an increase in vegetable and fruit wastes will cause higher C/N ratio and reduces both, the pH value and electrical conductivity; hence, reduces the compost quality. This ultimate aim is to minimise C/N ratio, maximise pH value, and maximise electrical conductivity. In order to compromise between the conflicting goals, the optimal settings of both vegetable and fruit wastes are in the middle intervals between 23.18% and 34.34% in the experiment, respectively. An increase in meat waste and cow manure drastically increases the pH value and electrical conductivity which exhibits minimal effect on the C/N ratio. Thus, the optimal setting of meat waste is at 36.46% and cow manure is at 6.01% in the experiment.

The optimum proportion of food wastes with cow manure obtained from the optimization plot was employed to validate the models developed for the responses. The predicted response for C/N ratio is 21.19, pH value is 7.92, and electrical conductivity is 0.97 dS/m which are close to the targeted responses of C/N ratio (21.0), pH (8.0), and electrical conductivity (1.0 dS/m), respectively.

CONCLUSION

Each food waste substrate, *e.g.* the vegetable, fruit and meat wastes, and its bulking agent of dry leaves or cow manure exhibited different effects on the C/N ratio, pH and electrical conductivity of the compost produced. The vegetable and fruit wastes contributed to drastic reduction in pH value and electrical conductivity. The C/N ratio increased significantly with fruit waste. Contrarily, meat waste gave significant increase in pH level and electrical conductivity which are desirable for producing good quality compost. In general, addition of dry leaves or cow manure in food wastes composting has reduced the C/N ratio and increased both the pH value and electrical conductivity of the compost produced and this is helpful in building the characteristics of organic soil substitutes or biofertilizer. The pilot scale anaerobic digester can be used to produce consistent compost from food waste.

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