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Simplex-centroid mixture formulation for optimised composting of kitchen waste

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ABSTRACT

Composting is a good recycling method to fully utilise all the organic wastes present in kitchen waste due to its high nutritious matter within the waste. In this present study, the optimised mixture proportions of kitchen waste containing vegetable scraps (V), fish processing waste (F) and newspaper (N) or onion peels (O) were determined by applying the simplex-centroid mixture design method to achieve the desired initial moisture content and carbon-to-nitrogen (CN) ratio for effective composting process. The best mixture was at 48.5% V, 17.7% F and 33.7% N for blends with newspaper while for blends with onion peels, the mixture proportion was 44.0% V, 19.7% F and 36.2% O. The predicted responses from these mixture proportions fall in the acceptable limits of moisture content of 50% to 65% and CN ratio of 20–40 and were also validated experimentally.

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1. Introduction

Waste has become a major problem to this world due to the increasing population, urbanisation, intensive agriculture and industrialization. Some 60% of the world's population is expected to live in the cities by 2020 (Bhatt, 2009). Based on the nature of mankind, people will produce kitchen waste everyday and everywhere no matter how much it is. Kitchen waste consists of considerable quantities of food processed and prepared for human consumption and all other constituents of the refuse like plastics and paper. While people give attention to recycle inorganic wastes such as plastics, glass and papers, the organic waste can be recycled into compost. This interpretation is similar with Veeken and Hamelers (1999), who found that the kitchen waste is rich in organic material and possesses more than 90% of biodegradability. As such, composting of kitchen waste can be an effective method to reduce waste in landfills which helps to conserve the environment.

In the context of composting, an optimum value of moisture content enables bacterial action to work as water acts as a medium for bacteria to become active and survive. Too high a moisture content will close the air pores, reduce the oxygen content and consequently turns composting into a fermentation process. Horiuchi et al. (2004) in their work of onion residues composting suggested that the moisture content has to be properly determined to maintain proper oxygen transfer in composting material. Nevertheless, if there is excessive water during a composting process, the leachates can be recovered and recycled for mixture rewetting (Laos et al., 2002). Previous studies have reported different ranges of optimum moisture content depending on the type of waste, *i.e.* 50–65% for olive pomace, poultry manure and wheat straw (Arvanitoyannis and Kassaveti, 2006), 61.8–64.2% for food waste, cow manure, mulch hay and wood shavings (Cekmecelioglu et al., 2005), 45–60% for exhausted olive cake, poultry manure and sesame bark (Sellami et al., 2008), and 65–80% for fresh vegetable processing waste (Stabnikova et al., 2005).

The optimum value of the carbon-to-nitrogen ratio (CN ratio) is also the other essential factor for microorganisms to perform the decomposition of organic wastes during a composting process (Qdais and Hamoda, 2004). Carbon provides the cellulose needed by the composting bacteria for conversion to sugars and heat. The carbon sources for microorganisms usually come from bulking agents such as sawdust and wood chips (Laos et al., 2002). Nitrogen provides the most concentrated protein, which allows the compost bacteria to thrive. Chang and Hsu (2008) have conclusively shown that substrate containing more protein has bacteria growing more rapidly and acids consumed faster rending a composting process which needs less time for maturity, produces more carbon dioxide, achieves higher temperatures during composting process and higher pH values at the end (Chang and Hsu, 2008). The initial CN ratio of the material must be between 25:1 and 35:1 (Cekmecelioglu et al., 2005) to avoid the production of offensive odours due to the high nitrogen content, which can mineralize into ammonia (Qdais and Hamoda, 2004) and the difficulties of the material to attain the thermophilic stage if it has too low CN ratio (Arvanitoyannis and Kassaveti, 2006). High CN ratio values will also lower the biodegradation rate which results a longer time for composting process (Qdais and Hamoda, 2004; Arvanitoyannis and Kassaveti, 2006).

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Since the initial moisture content and the CN ratio are two essential factors for a composting process, the correct formulation is necessary for commencing of the composting process. A systematic method of mixture optimisation can be used to generate the individual portion of each substrate instead of the trial-and-error method. The common sense and the trial-and-error method to get the best mixture (Sánchez-Arias et al., 2008) could be time consuming and require higher costs if results are not achieved after two to three replication. Besides in composting (Cekmecelioglu et al., 2005; Chang and Hsu, 2008), the mixture design has also been utilised to optimise mixture proportions in the food industry (Rehman et al., 2007), the pharmaceutical industry (Huang et al., 2005; Mura et al., 2005) and in engineering (Brandvik and Daling, 1998; Santafé-Moros et al., 2005). The objective of this paper is to find the optimum formulation of kitchen waste consisting vegetable scraps (V), fish processing waste (F), and newspaper (N) or onion peels (O) for composting with aid of commercial softwares *i.e.* the MINITAB and Expert-Design.

2. Methods

2.1. Materials

The vegetable scraps and fish processing waste used were ensured its homogeneity as the composition of kitchen waste depends on the eating habits and varies significantly from day to day. Spinach (*Spinacia oleracea* L.) from the family of Amaranthaceae, can be found mostly in subtropical and tropical regions and Indian mackerels (*Rastrelliger Kanagurta* C.) from the family of Scombridae, commonly found in the Indian and West Pacific oceans, and their surrounding areas were bought from a local market. The root of spinach and ¾ of its stem were chopped into maximum length of 2 cm. The unused parts of mackerels were removed and ground using a kitchen blender (PB-323T, Pensonic, Malaysia). The onion (*Allium cepa* L.) peels, from the family of Alliaceae, widely distributed and cultivated in Europe and North America were obtained from a grocery shop and the old newspapers were ground using a knife-blade lab grinder (Dickson DFT-150, China) in order to get a uniform mixture for obtaining a consistent blend. Blending of mixtures was done using a kitchen blender (PB-323T, Pensonic, Malaysia). Each substrate, *i.e.* vegetable scraps, fish processing waste, newspaper and onion peels were individually determined for their moisture, carbon and nitrogen content, as well as carbon-to-nitrogen (CN) ratio to verify the ability of these substrates acting as carbon and nitrogen source, and as bulking agent.

2.2. Mixture design

Two types of blends, A and B were produced to study on its optimum initial conditions of moisture content and carbon-to-nitrogen (CN) ratio for desired composting process. Blend A consisted of vegetable scraps, fish processing waste and newspaper while Blend B contained vegetable scraps, fish processing waste and onion peels. The MINITAB® Release 14 (Minitab Inc., US) software was used in determining the optimum proportions for each kitchen waste blend. The simplex-centroid mixture design was chosen for the experiments because all the components have the same range, which between 0–100, and there were no constrains on the design space. The simplex term refers to the geometry form of a triangle when in two-dimensions and tetrahedron when in three-dimensions. The simplex-centroid is more uniformly distributed in the interior of the triangle and helps to detect curvature of response surface. All proportions of all substrates in each mixture were sum to 100% for a mixture load of 100 g. The Minitab software generated 13 runs for each blend where the moisture content and CN ratio were determined experimentally for each run prior to generating the contour maps from the fitted regression models with the software.

2.3. Response analyses

The searched responses in this study were moisture content and CN ratio. Analyses were done in triplicates and means are reported. The moisture content was determined using the conventional air oven method (Kato and Miura, 2008; Mohee et al., 2008; Unmar and Mohee, 2008), where each fresh sample was oven-dried at 105 °C until it achieved a constant weight (approximately for 24 h). The dried sample was then ground into a fine powder for finding the CN ratio. The percentage of moisture content was calculated following Eq. (1) (Schwab et al., 1994)

$$\%\text{Moisture} = \frac{\text{Weight}_{\text{Wet}} - \text{Weight}_{\text{Dry}}}{\text{Weight}_{\text{Wet}}} \times 100 \tag{1}$$

The ash content was measured using the dry ashing method (Mohee et al., 2008; Unmar and Mohee, 2008) to obtain the volatile solids content prior to acquiring the total organic carbon content. Clean and empty crucibles were placed in a muffle furnace for 1 h at 550 °C to ensure that there are no other carbon particles that can affect the readings. After cooling the crucibles in a desiccator, 2.5 g of blended samples were weighed into the crucibles and the samples were burned in the furnace at 550 °C for about 2 h or until no stains of black carbon particles. The total organic carbon content was calculated following Eqs. (2)–(4) (Richard, 2007; Mohee et al., 2008)

$$\%\text{Ash} = \frac{\text{Weight}_{\text{Initial}} - \text{Weight}_{\text{Final}}}{\text{Weight}_{\text{Initial}}} \times 100 \tag{2}$$

$$\%\text{Volatile Solid} = 100 - \%\text{Ash} \tag{3}$$

$$\%\text{Total Organic Carbon} = \frac{\%\text{Volatile Solid}}{1.8} \tag{4}$$

The total nitrogen determination was measured using the Micro Kjeldahl method (Mohee et al., 2008; Unmar and Mohee, 2008), where 0.15 g of blended sample was weighed and placed in a boiling tube. For the blank, no sample was used. 0.8 g of mixed catalysts was first added into the boiling tube, then 2.5 ml of concentrated sulphuric acid was added before heating slowly on a heating coil under fume hood for the digestion process to break all the bonds in the sample. The contents were boiled until the solution became clear and gave a blue-green colour. After cooling to about 40 °C, 5 ml of distilled water was added and the digested product was transferred into a distillation tube. Five millilitres of distilled water was added to wash any residues left inside the boiling tube. Ten millilitres of 45% of Natrium Hydroxide (NaOH) solution was added slowly to separate the two layers of solution. The distillation tube was fixed to the condenser neatly. Ten millilitres of 2% boric acid and three drops of indicator were added into a conical flask. The conical flask was placed on the distillate platform and the tip of distillation tube was immersed into the acid solution. The distillation unit was run for 120 s. The unreacted boric acid was titrated with 0.05 N Sulphuric Acid (H_2SO_4) until neutral and the same procedure was repeated for the blank sample. The percentage of nitrogen content was calculated following Eq. (5) (Codell and Verderame, 1954).

$$\%\text{Total Nitrogen} = \frac{1.4(R - S)N}{W} \tag{5}$$

where R is volume of H_2SO_4 to titrate boric acid (ml), S is volume of H_2SO_4 to titrate blank (ml), W is weight of sample (g), and N is normality of H_2SO_4 = 0.05 N.

The carbon-to-nitrogen ratio was determined by dividing the total organic carbon content to the total nitrogen content.

3. Results and discussion

3.1. Characterisation of composting materials

Table 1 shows the moisture, carbon and nitrogen contents, and the CN ratio for individual composting substrate used. The vegetable scraps have the highest moisture content, followed by the fish processing waste, onion peels and newspaper. As fish processing waste owns high protein content (Rahmi et al., 2008) as well as nitrogen content, it makes a good nitrogen source that supplies nutrient to composts. The CN ratio for newspaper is extremely high while fish processing waste possesses the lowest CN ratio. The newspaper and onion peels could be a carbon source due to relatively higher carbon contents of 50.56% and 50.27%, respectively.

3.2. Fitting for the best model

Table 2 presents the results of mixture design studies. The independent variables and the runs were generated and arranged randomly by the Minitab software. To minimise variance, the moisture content and CN ratio for each run were triplicated. Both the independent and dependent variables were fitted to linear, quadratic, special cubic, full cubic and special quartic models and residuals plots were generated to check the goodness of model fit. Tables 3 and 4 present the important values that were examined to determine the adequate model for each dependent variable. Since the standard deviation is important for checking data distribution, the predicted sum of squares for measuring the model's predictive ability and the predicted R-squared were calculated and compared. The best model has low standard deviation and predicted sum of squares, and high predicted R-squared (Cornell, 2002). Following these guides, the linear model was found the best fitted for the moisture content of both blends while the quadratic model was adequately fitted to the response of CN ratio for both blends.

3.3. Modelling of initial moisture content and CN ratio

Eqs. (6)–(9) show the optimised mixture proportion equations of Blend A and Blend B

$$Y_{\mathrm{Am}} = 92.726x_1 + 75.326x_2 + 4.862x_3 \quad (6)$$

$$Y_{\mathrm{Bm}} = 92.85x_1 + 75.52x_2 + 11.66x_3 \quad (7)$$

$$Y_{\mathrm{Acn}} = 14.9x_1 + 8.2x_2 + 281.6x_3 + 17.7x_1x_2 - 273.3x_1x_3 - 509.3x_2x_3 \quad (8)$$

$$Y_{\mathrm{Bcn}} = 12.28x_1 + 7.02x_2 + 60.22x_3 - 16.07x_1x_2 + 39.5x_1x_3 - 49.27x_2x_3 \quad (9)$$

Eqs. (6) and (7) are linear terms for moisture content of Blend A and Blend B, respectively. Eqs. (8) and (9) are the quadratic terms for CN ratio of Blend A and Blend B, respectively. Y_{Am} is initial moisture content (%) for Blend A, Y_{Bm} is the initial moisture content (%) for Blend B, Y_{Acn} is the inital CN ratio for Blend A, and Y_{Bcn} is the initial CN ratio for Blend B. The numbers refer to the regression coefficients listed in Table 5, and x_1, x_2 and x_3 are the three independent variables, each representing vegetable scraps, fish processing waste and newspaper or onion peels, respectively.

Table 2
Mixture design and response values for Blends A and B.

Run	Independent variables, x_{ij}			Dependent variables, Y	
	Vegetable scraps (%)	Fish processing waste (%)	Newspaper or onion peels (%)	Moisture content (%)	CN ratio
Blend A					
1	16.667	16.667	66.667	26.12	62.7
2	0.000	50.000	50.000	40.05	24.2
3	100.000	0.000	0.000	93.14	13.0
4	0.000	0.000	100.000	6.73	297.6
5	33.333	33.333	33.333	59.13	24.2
6	0.000	100.000	0.000	75.72	4.7
7	50.000	0.000	50.000	48.02	89.8
8	0.000	100.000	0.000	75.27	4.8
9	16.667	66.667	16.667	66.61	10.5
10	100.000	0.000	0.000	92.97	13.2
11	0.000	0.000	100.000	6.27	278.7
12	50.000	50.000	0.000	83.87	5.8
13	66.667	16.667	16.667	75.40	23.8
Blend B					
1	50.000	50.000	0.000	84.74	6.0
2	0.000	100.000	0.000	76.25	5.9
3	66.667	16.667	16.667	76.92	16.7
4	100.000	0.000	0.000	93.68	12.6
5	50.000	0.000	50.000	50.65	50.3
6	0.000	100.000	0.000	76.08	5.7
7	33.333	33.333	33.333	55.60	22.6
8	0.000	0.000	100.000	11.53	59.6
9	100.000	0.000	0.000	93.51	12.7
10	0.000	50.000	50.000	44.72	22.3
11	16.667	16.667	66.667	38.63	36.0
12	16.667	66.667	16.667	65.92	16.2
13	0.000	0.000	100.000	11.84	62.2

Table 3
Model summary statistics for moisture content and CN ratio of Blend A.

Source	Standard deviation, S	Regression, R-Sq (%)	Predicted regression, R-Sq (pred)	Adjusted regression, R-Sq (adj) %	Predicted sum of squares, PRESS
Moisture content					
Linear	1.8733	99.68	99.51	99.61	53.0333
Quadratic	2.0002	99.74	99.34	99.56	71.5906
Special cubic	2.1427	99.75	96.38	99.49	392.7090
Full cubic	1.5055	99.92	86.04	99.75	1515.7400
Special quartic	1.5055	99.92	86.04	99.75	1515.7400
CN ratio					
Linear	50.7029	79.36	64.35	75.23	44392.2
Quadratic	19.9317	97.77	93.37	96.17	8254.73
Special cubic	21.5267	97.77	67.64	95.53	40305.6
Full cubic	9.2348	99.73	77.08	99.18	28543.7
Special quartic	9.2348	99.73	77.08	99.18	28543.7

Table 1
Percentage (%)[a] of moisture, carbon and nitrogen content, and CN ratio.[a].

Substrates	Moisture content (%)	Carbon content (%)	Nitrogen content (%)	CN ratio
Vegetable scraps	93.32 ± 0.33	37.87 ± 1.14	2.94 ± 0.14	12.87 ± 0.24
Fish processing waste	75.83 ± 0.43	42.60 ± 1.73	8.14 ± 1.24	5.30 ± 0.61
Newspaper	6.50 ± 0.32	50.56 ± 0.02	0.18 ± 0.01	288.15 ± 13.36
Onion peels	11.69 ± 0.22	50.27 ± 0.63	0.83 ± 0.01	60.91 ± 1.82

[a] Data are in mean and standard deviation.

Table 4
Model summary statistics for moisture content and CN ratio of Blend B.

Source	Standard deviation, S	Regression, *R*-Sq (%)	Predicted regression, *R*-Sq (pred) %	Adjusted regression, *R*-Sq (adj) %	Predicted sum of squares, PRESS
Moisture content					
Linear	1.9258	99.60	99.47	99.52	48.8388
Quadratic	2.0632	99.68	99.14	99.44	79.0690
Special cubic	2.0107	99.74	96.33	99.47	336.9420
Full cubic	1.6487	99.88	79.85	99.64	1849.3000
Special quartic	1.6487	99.88	79.85	99.64	1849.3000
CN ratio					
Linear	5.9967	92.67	89.44	91.20	518.0090
Quadratic	3.9280	97.80	91.37	96.22	423.4020
Special cubic	3.9664	98.08	71.32	96.15	1406.4500
Full cubic	1.3121	99.86	87.56	99.58	609.7770
Special quartic	1.3121	99.86	87.56	99.58	609.7770

The regression coefficients for all the terms in the optimised models are summarised in Table 5. The magnitudes of the coefficients for the three materials indicate that the vegetable scraps (92.73 and 92.85) have higher moisture content than fish processing waste (75.33 and 75.52), newspaper (4.86) and onion peels (11.66). For CN ratio, the coefficients values for the three materials show that the fish processing waste (8.20 and 7.02) have low CN ratio compared to vegetable scraps (14.90 and 12.28), newspaper (281.60) and onion peels (60.22). Since moisture content for both the blends fitted the linear model, the coefficients for two-blend mixtures of b_{12}, b_{13} and b_{23} did not exist. Positive coefficients for a two-blend mixtures means that the two materials are complementary and if the two-blend mixtures have negative coefficients, the two materials are opposed towards one another. The mixture containing vegetable scraps (b_{13}) or fish processing waste (b_{23}) with either newspaper or onion peels produced significant CN ratio with $p < 0.05$. This suggests that composting of food waste is recommended using either vegetable scraps or fish processing waste singly combined with newspaper or onion peels. The *R*-squared (R^2) more than 97% indicate that the models chosen fitted the data very well.

3.4. Mixture proportion optimisation

Using the Minitab software, the optimisation calculations were performed to find an optimum mixture proportions for commence of composting process. Based on the combined optimum initial moisture content and CN ratio of 60 and 30%, respectively, the finest mixture proportions that met the composite desirability of approximately one was obtained. Figs. 1 and 2 show that both blends A and B gave similar results for the contour and surface plots. The newspaper and onion peels offer greater effect in adjusting the moisture content. The surface plots show that the lowest moisture content was obtained when mixed with a large amount of newspaper (Fig. 1) or onion peels (Fig. 2).

Table 5
Regression coefficients, R^2 for two dependent variables of two blends.

Coefficient	Moisture content		CN ratio	
	Blend A	Blend B	Blend A	Blend B
b_1	92.73	92.85	14.90	12.28
b_2	75.33	75.52	8.20	7.02
b_3	4.86	11.66	281.60	60.22
b_{12}	–	–	17.70	−16.07
b_{13}	–	–	−273.30*	39.50*
b_{23}	–	–	−509.30**	−49.27*
R^2	99.68	99.60	97.77	97.80

Subscripts: 1 = vegetable scraps; 2 = fish processing waste; 3 = newspaper or onion peels.
Blend A consists of vegetable scraps, fish processing waste and newspaper,
Blend B consists of vegetable scraps, fish processing waste and onion peels.
* Significant at 0.05 level.
** Significant at 0.001 level.

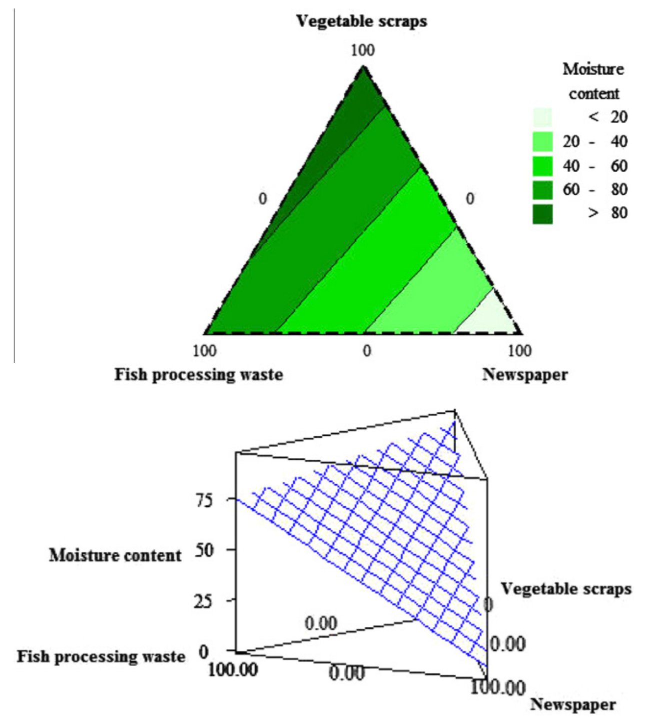

Fig. 1. Mixture contour plot (above) and surface plot (below) of moisture content for Blend A.

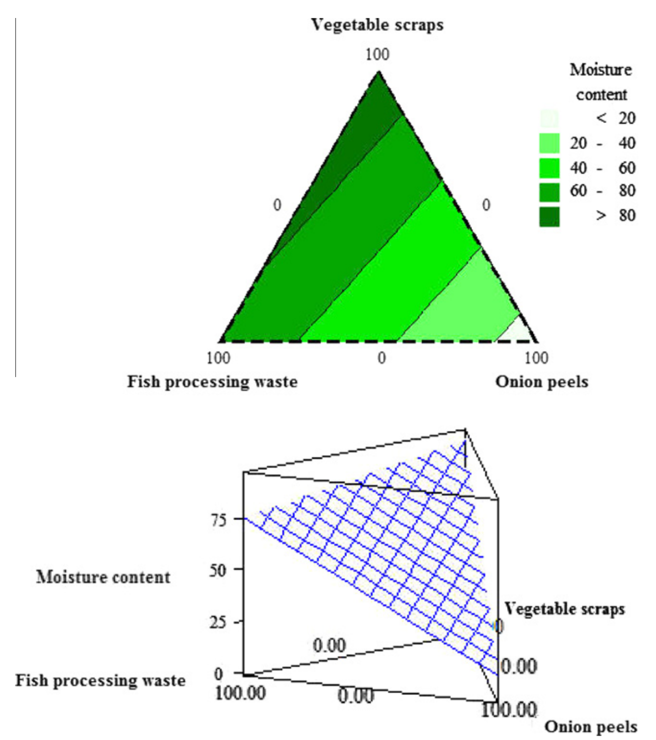

Fig. 2. Mixture contour plot (above) and surface plot (below) of moisture content for Blend B.

Fig. 3 shows that the area of the optimum initial CN ratio (30) is located at the middle of the contour plot for Blend A. Almost all amounts of vegetable scraps gave optimal CN ratio. The CN ratio increases when larger amount of the newspaper is combined but decreases when large amount of fish processing waste is used. The contour plot in Fig. 4 suggests that the highest CN ratio is obtained when the amount of onion peels is large. The lowest CN ratio was achieved when the mixture contained more fish processing waste, little or no onion peels, and nearly all or no vegetable scraps.

Fig. 5 points up two overlaid contour plots for Blends A and B, respectively, which the mixture components used are three factors. The feasible regions that satisfy both optimum response variables settings are illustrated as the white area inside each plot. These overlaid contour plots are important for finding the best mixture proportions for optimising the initial moisture content and CN ratio of the blends and any combinations that fall inside the white area are suitable for composting. The shaded areas on the graphical optimisation plot refer to responses which do not meet the selection criteria.

For response optimisation, the combined goals for moisture content of 60% and CN ratio of 30 was satisfied by mixture proportions given in Table 6. These solutions provided moisture content of 60% for both blends, and CN ratio of 29.9931 and 29.9980 for Blend A and B, respectively. These predicted responses were chosen because they gave the highest composite desirability, which are 0.9997 for Blend A and 0.9999 for Blend B, than other acceptable optimum combinations that fall in the feasible regions in Fig. 5. The predicted responses and the composite desirability near to one indicate that the optimum initial moisture content and CN ratio was met. Zero composite desirability denotes that one or both responses are outside their acceptable limits.

3.5. Validation of the model

The experimental data were fitted into the Eqs. (6)–(9) and the optimum proportions were found to be 48.5% of vegetable scraps, 17.7% of fish processing waste and 33.7% of newspaper for Blend A, and 44.0% of vegetable scraps, 19.7% of fish processing waste and 36.2% of onion peels for Blend B. At these optimum formulations, the moisture content was 61.48% for Blend A and 58.13% for Blend B, which are reasonably close to the predicted value of 60%. These results are comparable to those of Cekmecelioglu et al. (2005) and

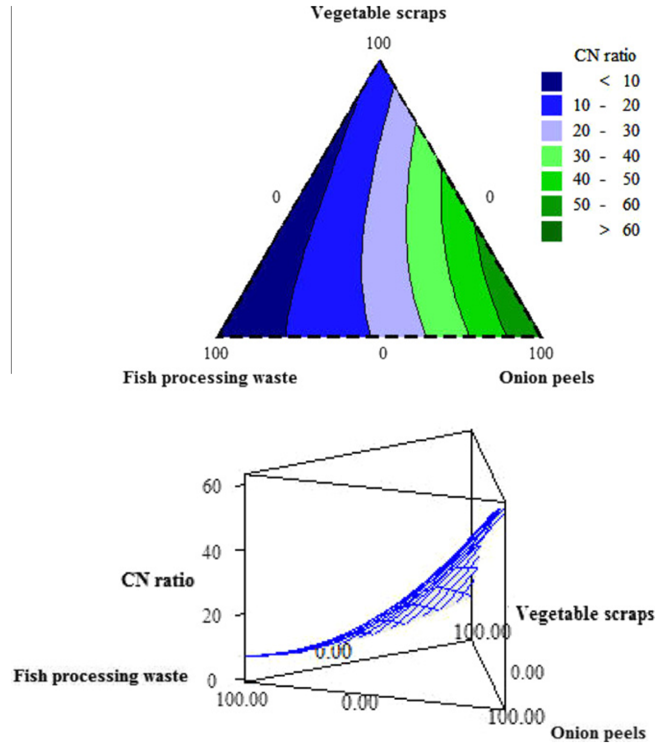

Fig. 4. Mixture contour plot (above) and surface plot (below) of CN ratio for Blend B.

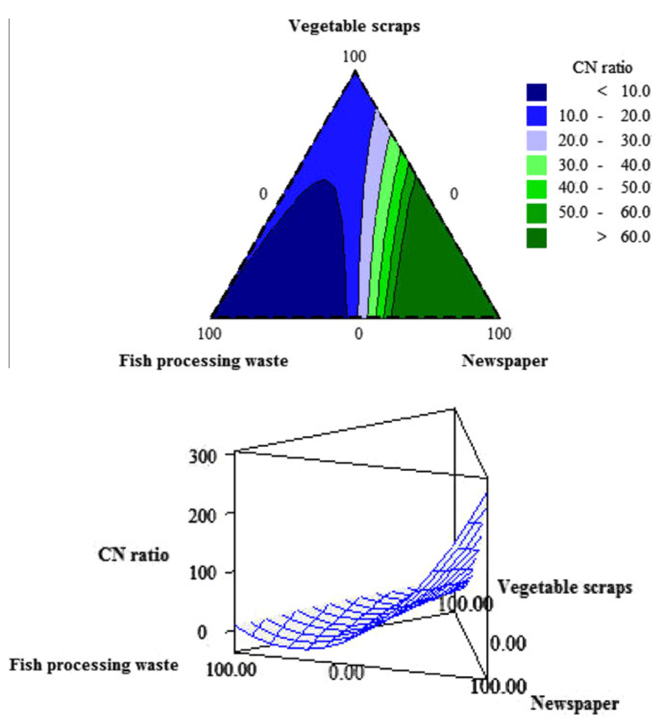

Fig. 3. Mixture contour plot (above) and surface plot (below) of CN ratio for Blend A.

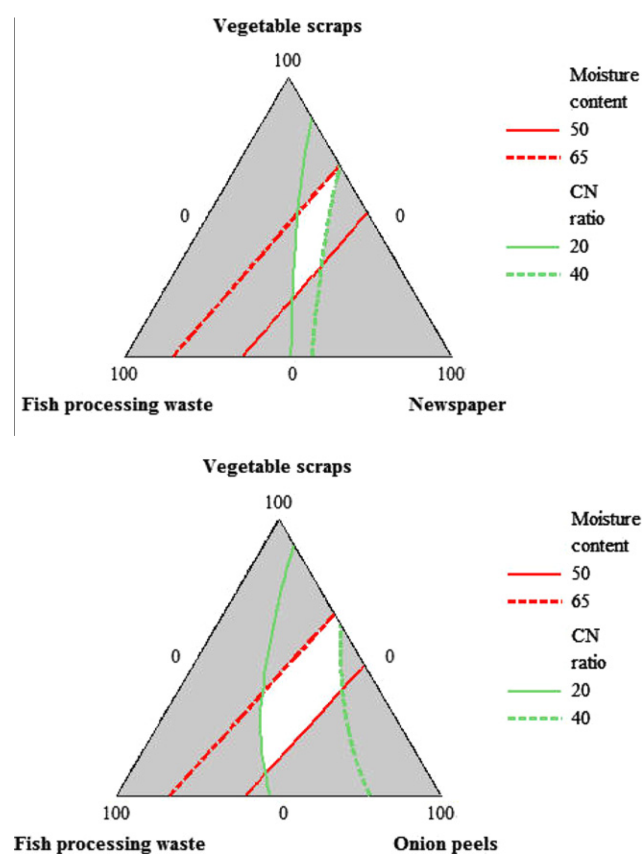

Fig. 5. Overlaid contour plot of moisture content and CN ratio for Blend A (above) and Blend B (below).

Table 6
Optimum mixture proportions for each blend.

Components	Proportions (%)	
	Blend A[a]	Blend B[b]
Vegetable scraps	48.5295	44.0217
Fish processing waste	17.7361	19.7360
Newspaper or onion peels	33.7344	36.2423

[a] With newspaper.
[b] With onion peels.

Sellami et al. (2008) findings, whom reported 61.8–64.2% and 45–60%, respectively. The CN ratio is quite close to the predicted value of 30, where Blend A gave 33.3 and Blend B gave 30.5. Although the CN ratios were slightly higher than the predicted value, they are still in the range of ideal CN of 20–40 for composting. The moisture content of 50–65% (Arvanitoyannis and Kassaveti, 2006; Chang et al., 2006) and CN ratio of 20–40 (Chang et al., 2006) were ideal conditions for composting.

4. Conclusions

The proportion of each substrate is important to ensure the efficiency of composting. Different amounts of vegetable scraps, fish processing waste, newspaper and onion peels gave effect to the initial moisture content and CN ratio of the kitchen waste. The mixture design used for predicting this waste recipe prior to composting studies through an optimisation process provides the best condition for degradation process take place.

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