Environ Monit Assess (2015) 187: 217
DOI 10.1007/s10661-015-4430-9

Critical factors and their effects on product maturity in food waste composting

Zhong Li · Guohe Huang · Hui Yu · Yang Zhou · Wendy Huang

Received: 21 July 2014 / Accepted: 12 March 2015 / Published online: 31 March 2015

Abstract Product maturity represents the efficiency of composting performance, and it calls for high attention in food waste composting. In this study, a 2^{4-1} fractional factorial design method combined with well-controlled experiments was introduced to characterize the effects of system factors (i.e., C/N ratio, aeration rate, starting culture amount, and coal ash amendment) on product maturity of food waste composting. The compost maturity was synthetically evaluated by developing a Mamdani fuzzy rule-based inference system. Temperature index, O_2 uptake rate, ammonium, OM loss, C/N ratio, and ash content were chosen as indicators of the fuzzy multicriterion maturity evaluation. Evaluation results of compost maturity for the eight experiment runs demonstrated that the proposed method is capable of evaluating the compost maturity in food waste composting. The effect analyses indicated that the starting culture amount and aeration rate contributed the most to the compost maturity in this study. The results could provide decision support for the process control in food waste composting management.

Keywords Food waste composting · Fractional factorial design · Fuzzy inference system · Maturity · Waste management

Introduction

Food waste is the largest component of municipal solid waste streams after the recyclables are separated (Yu and Huang 2009; Getahun et al. 2014). Composting provides a valuable way of mitigating pollution and recycling nutrients in solid waste (Beck-Friis et al. 2000; Xiao et al. 2007; Gunalay et al. 2012; Saha et al. 2013), and it is gaining more and more attention as an

---

Z. Li · G. Huang (✉) · Y. Zhou
Institute for Energy, Environment and Sustainability Research, UR-NCEPU, University of Regina, Regina, SK S4S 0A2, Canada
e-mail: huang@iseis.org

Z. Li
e-mail: li395@uregina.ca

Y. Zhou
e-mail: zhou206y@uregina.ca

G. Huang
Institute for Energy, Environment and Sustainability Research, UR-NCEPU, North China Electric Power University, 102206 Beijing, China

H. Yu
Department of Civil and Environmental Engineering, Temple University, Philadelphia, PA 19122, USA
e-mail: bestyuhui@gmail.com

W. Huang
Department of Civil Engineering, McMaster University, Hamilton, ON L8P 2R3, Canada
e-mail: wendywanzhihuang@gmail.com

effective alternative for food waste treatment (Smårs et al. 2002; Quirós et al. 2014).

An essential method to assess compost quality is the evaluation of maturity (Fu 2004; Zhang et al. 2008). Maturity is a comprehensive evaluation indicator that uses various parameters, such as oxygen demand, reheating potentials, CO_2 generation rate, organic acid concentration, and organic materials loss, to reflect the specific metabolism levels and to reveal the compost qualities (Komine et al. 2004; Tognetti et al. 2007). Over the past decades, a number of methods, including principal component analysis, integrated factor analysis and canonical correlation analysis, were proposed to evaluate soil/compost quality (Andrews and Carroll 2001; Zhang et al. 2014). More recently, fuzzy inference systems, developed based on the fuzzy set theory, have been recognized as an appealing evaluation method (Wang et al. 2009; Li et al. 2013a, b; Miao et al. 2014; Xu et al. 2014). So far, there is no one objective and uniform maturity definition (Andrews and Carroll 2001; Komine et al. 2004). Evaluation of compost quality often involves subjective description, where fuzzy inference systems could be used to effectively encode expert knowledge, and to perform nonlinear mapping between physical, chemical, and biological indicators and compost maturity under uncertainties (Cherkassky 1998; Lv et al. 2010; Li et al. 2013a, b). However, the previous studies mainly focused on exploring tools and techniques for the maturity evaluation, and there were few studies focusing on the effects of various system factors on compost maturity (Tognetti et al. 2007; Senthil Kumar et al. 2014).

Raw material factors such as the carbon to nitrogen (C/N) ratio, starting culture, amendment, and moisture, as well as other factors such as temperature, pH, and aeration, are considered as the main factors in composting processes (Saha et al. 2013; Araujo et al. 2015). Almost all of the system factors that affect the composting process are potential influencing factors of the compost maturity (Nair et al. 2006; Yu et al. 2010). Previous efforts have been made in investigating the effects of the aforementioned factors on individual compost quality indicators, such as microbial activity, organic acid variation, and nitrogen transformation (Humer and Lechner 1999; Sun 2006; Yu et al. 2010; Pisa and Wuta 2013). However, there were very few studies on the effects of these factors or their interactions on the comprehensive indicator of compost product quality, i.e., compost maturity. Factorial analysis provides a feasible method for studying the effects of individual variables as well as their interactive effects on the responses (Box et al. 1978). Crucial factors and/or factor combinations can be identified in terms of factorial design (Montgomery 2008). Applications of this method have stated its efficiency for supporting multivariate inference of the interactive effects in many fields, including composting researches (Leiva et al. 2003; Li et al. 2008; Zhou et al. 2013). It is thus desired to investigate how the system factors exert their influences and interactive effects in food waste compost products through factorial analysis.

Therefore, the objective of this study is to systematically investigate the composting factors' effects on the compost maturity. Four system factors (C/N ratio, aeration rate, starting culture amount, and amendment) will be examined in terms of their effects on product maturity in food waste composting. A 2^{4-1} fractional factorial analysis approach will be applied to design the food waste composting experiments, and eight designed experiment runs will be set up. A synthetic multi-criterion evaluation method based on the Mamdani type fuzzy inference system will be developed and applied to assess the compost maturity.

Methods

Experiment design

In general, factorial designs are most efficient for the experiments involving effects of two or more factors (Montgomery 2008). A complete factorial design contains all possible settings of the experimental factors. When an experimental procedure with k variables is analyzed, determination of the influence of the k variables through a complete two-level factorial design calls for 2^k individual experimental runs. Information on the main effects and low-order interactions may be also obtained by running only a fraction of the complete factorial experiments (Montgomery 2001). Fractional factorial design has been widely used in many fields to enable the goals of the experiment to be met with the least cost, shortest time, or most effective use of resources (Gunst and Mason 2009). The objective of this study is to investigate the magnitude and direction of the system factors' influences on compost maturity, while the high-order interactions among these factors are assumed negligible. Therefore, a complete factorial design was not necessarily needed and a fractional factorial design was adopted. Four factors, which are C/N ratio (*A*), aeration rate (*B*), starting culture amount (*C*), and coal ash amendment (pH control agent) (*D*), were chosen and set at two levels (Table 1). The high-level (+) and low-level (−) values of these factors were determined based on literature review.

In order to decrease the required number of experiments without considerable loss of information, a 2^{4-1} design with $I=ABCD$ was used (Fries and Hunter 1980). Eight runs of experiments were carried out. To construct this design, a basic 2^3 design was first initiated, as shown in the first three columns of Table 1. The equation $I=ABCD$ was solved to define the fourth factor's (*D*) level. The level of *D* in each run is the product of the plus and minus signs in columns *A*, *B*, and *C*. The process is illustrated in Table 1.

With the aforementioned relations, each effect can be aliased with a three-factor interaction, and each two-factor interaction can be aliased with another two-factor interaction. These alias relationships are listed in Eqs. (1)–(7):

$$A = A^2BCD = BCD \tag{1}$$

$$B = AB^2CD = ACD \tag{2}$$

$$C = ABC^2D = ABD \tag{3}$$

$$D = ABCD^2 = ABC \tag{4}$$

$$AB = CD \tag{5}$$

$$AC = BD \tag{6}$$

$$BC = AD \tag{7}$$

Furthermore, run 4 was performed in duplicate (i.e., runs 4A and 4B) to test the reproducibility of reactor performance, making nine process runs of experiments in all.

Food waste composting

According to the 2^{4-1} fractional factorial design, eight runs of experiments (plus one quality control run) were designed using bench-scale reactors. Potato, carrot, ground pork, steamed rice, and leaves were used to simulate food waste. All materials were obtained from a local grocery store and chopped into cubes with approximately 5 mm in diameter using a food processor. Maturate compost was added as the starting culture and well mixed with the food compositions. Initial states of the raw materials of the nine experimental runs are listed in Table 2.

A schematic diagram of the composting reactor is presented in Fig. 1. The reactor was made from a cylindrical PVC container with a diameter of 30 cm, a depth of 45 cm, and an effective volume of approximately 31 L. Three layers of insulator (i.e., heavy-duty aluminum, foam, and fiberglass from inner to outer layers) were added on the reactor to prevent heat loss. An air inlet connected with a vacuum pump was installed at the bottom of the reactor, an outlet was also installed at the

Table 1 The 2^{4-1} fractional factorial design

Run	C/N ratio (*A*)	Aeration rate (L/min kg) (*B*)	Starting culture amount (*C*) (%)	Coal ash amendment (*D=ABC*)	Treatment combination
1	15 (−)	0.3 (−)	5 (−)	With (−)	(l)
2	15 (−)	1 (+)	20 (+)	With (−)	*bc*
3	30 (+)	0.3 (−)	20 (+)	With (−)	*ac*
4	15 (−)	0.3 (−)	20 (+)	Without (+)	*cd*
5	30 (+)	1 (+)	20 (+)	Without (+)	*abcd*
6	30 (+)	1 (+)	5 (−)	With (−)	*ab*
7	15 (−)	1 (+)	5 (−)	Without (+)	*bd*
8	30 (+)	0.3 (−)	5 (−)	Without (+)	*ad*

Table 2 Initial states of raw composting materials

	Run	1	2	3	4A	4B	5	6	7	8
Physical and chemical characteristics	Coal ash amendment (kg)	1.0	1.0	1.0	–		–	1.0	–	–
	pH	6.23	6.29	6.12	5.87	5.81	5.95	6.14	5.76	5.89
	Moisture content (%)	52.65	51.18	55.42	57.15	59.37	64.19	59.23	63.75	64.27
	Ash content (%)	32.19	34.92	32.95	6.32	6.43	7.10	31.39	5.27	3.20
	C/N ratio	15.05	16.23	31.94	15.40	17.72	32.55	30.55	16.21	31.90
	NH_4-N (mg/kg) (dry)	53.67	55.12	35.63	61.27	77.62	38.92	35.75	76.01	48.64
	NO_3-N (mg/kg) (dry)	4.22	5.33	10.32	5.48	5.54	8.21	9.56	8.55	4.62

bottom to collect leachate, an exhaust gas outlet was placed at the top to analyze oxygen content and ammonia, and a stainless steel stick was inserted to place thermometers for temperature monitoring. The ambient temperature was maintained at 20±1 °C. The composting materials were manually shoveled and stirred once a day, and then, three samples of approximately 50 g were randomly collected from each reactor for analyses of pH level, ash content, total carbon content, total nitrogen content, ammonium and OM loss. For a more detailed description of the analytical methods, refer to the previous work by Yu and Huang (2006).

Fuzzy synthetic evaluation method

The fuzzy synthetic evaluation process in this study is as follows: (1) six indicators were selected as the indicators of maturity, (2) the indicator values and maturity score were fuzzified using triangle membership functions, (3) weights of the indicators were assigned using the eigenvalue scaling method of the analytical hierarchy process approach, (4) the inference system was established using the Mamdani fuzzy method, and (5) defuzzification was conducted to transform fuzzy outputs of the inference system into a crisp output.

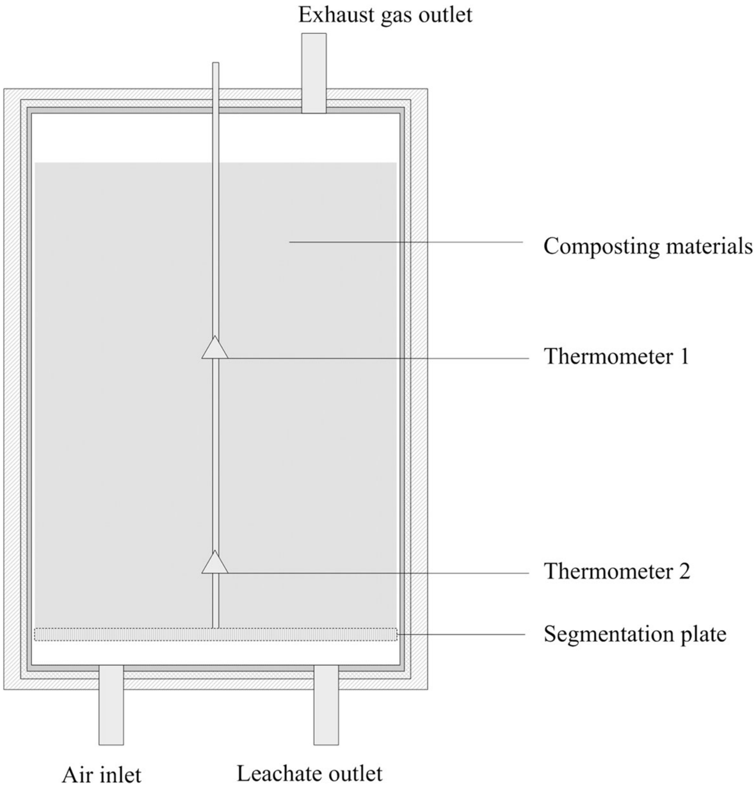


Fig. 1 Schematic diagram of the composting system

The selected indicators included temperature index (TI), O_2 uptake rate (O_2), ammonium (NH_4-N), OM loss, C/N ratio (C/N), and ash content (ash) (de Bertoldi et al. 1988; Nakasaki et al. 1993), where TI was proposed and defined to tackle the unevenly changing characterization of temperature evolution by Fu (2004). The six indicators comprehensively reflect the physical, chemical, and biological status, as well as humification degrees of the composts. Fuzzification of the six indicators and the output maturity were carried out by defining the corresponding membership functions that specify the degree to which a given input belongs to a set or is related to a concept, as shown in Fig. 2 (Bernal et al. 1998; Fu 2004).

To obtain weights of the six indicators, relative weights were first determined according to the description of relative importance for scales proposed by Saaty (1977). The reciprocal matrix of pairwise comparison of the relative importance was then built according to the relative weights (w_n) of six indicators in pairs, as presented in Eq. (8) (Cabala 2010).

$$A = \begin{bmatrix} 1 & 1 & 2 & 4 & 6 & 9 \\ 1 & 1 & 2 & 2 & 6 & 9 \\ 1/2 & 1/2 & 1 & 2 & 4 & 6 \\ 1/4 & 1/2 & 1/2 & 1 & 3 & 3 \\ 1/6 & 1/6 & 1/4 & 1/3 & 1 & 2 \\ 1/9 & 1/9 & 1/6 & 1/3 & 1/2 & 1 \end{bmatrix} \tag{8}$$

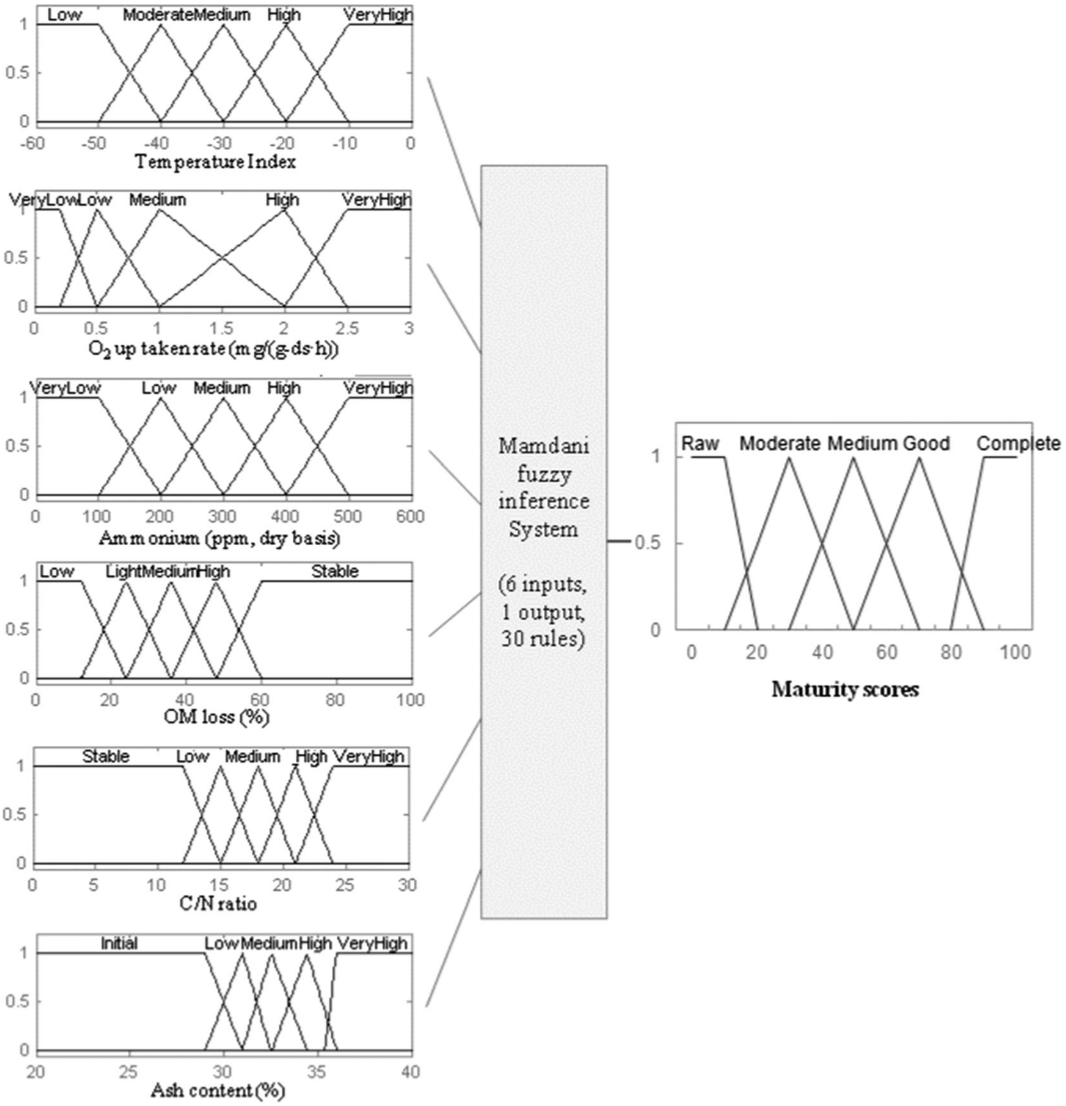


Fig. 2 Membership functions and hierarchy structure of the maturity evaluation system

According to Fu (2004) and Cabala (2010), the weight eigenvector can be obtained by unifying the eigenvector of matrix A. Thus, the normalized weight vectors were as follows:

$$W = [w_{\mathrm{TI}}, w_{\mathrm{O2}}, w_{\mathrm{NH4\text{-}N}}, w_{\mathrm{OM\ loss}}, w_{\mathrm{C/N}}, w_{\mathrm{Ash}}] = [0.3314, 0.2949, 0.1816, 0.1110, 0.0493, 0.0318] \quad (9)$$

To evaluate the reliability of the weight assignment, the index consistency (μ), defined as follows, was calculated.

$$\mu = \frac{\lambda_{\max} - n}{n-1} \quad (10)$$

where n is the number of indicators and $\lambda_{\max}$ is the nonzero eigenvalue of matrix A ($\lambda_{\max}$=6.0815). The closer to zero the μ value is, the more reliable the weight assignment is. In this study, the consistency is μ=0.0163, which indicates a reliable weight assignment (Saaty 1977).

Linguistic statements that describe the compost maturity were then written “IF-THEN” rules to be encoded using the Mamdani fuzzy inference method. Fuzzy logic operators “and” and “or” were defined as “MIN” and ”MAX”, respectively; the implication and aggregation methods were “MIN” and ”MAX”, respectively. More details about the reasoning process of Mamdani fuzzy inference can be found in the study of Mamdani and Assilian (1975). The hierarchy structure of the Mamdani fuzzy inference system for synthetic evaluation of compost maturity is presented in Fig. 2. Input sets with unclear boundaries can be mapped to crisp maturity scores (0~100) through the rule-based fuzzy inference.

Statistical analysis

The factors and interactions that had significant effects on the compost maturity were discussed based on fractional factorial analysis. To estimate an effect or to compute the sum of squares for an effect, the contrast associated with that effect was determined firstly (Box et al. 1978).

When the contrasts for each effect are computed, the effects and the sums of squares (SSs) can be estimated. Then, an analysis of variance can be undertaken to test the significances of main effects and interactions.

As for the unreplicated experiments as in this study, a simple examination of the normal probability plot of the effects can be used to test the significances of main effects and interactions (Daniel 1959). The plotted points falling along an imaginary straight line through (0, 0) indicate that the estimated effects can be attributed to normal random variability; the reciprocal of the slope for such a straight line gives an indication of the standard error of the estimated effects. The effects that were negligible would tend to fall along a straight line on the normal probability plot; significant effects would not lie along the straight line.

Results and discussion

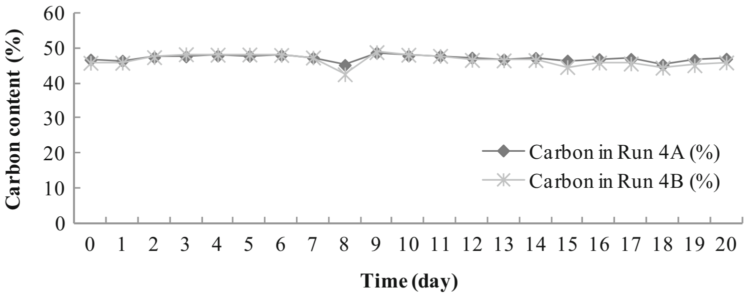
Reproducibility of reactor performance

The reproducibility of the experimental composting system was assessed through analyses of carbon and nitrogen contents as well as C/N ratio in duplicated experiments (runs 4A and 4B). Runs 4A and 4B were controlled with identical initial raw materials, additive input patterns, and reaction conditions. The temporal variations of carbon contents, nitrogen contents, and C/N ratio show that the processes in runs 4A and 4B developed similarly (Fig. 3). One-way ANOVA analysis was performed to test the reproducibility of reactor performance. The results of ANOVA test with a significance level of 0.05 are shown Table 3. P values of carbon contents, nitrogen contents, and C/N ratio in runs 4A and 4B are 0.171, 0.639, and 0.774, respectively. It is implied that the differences between the two runs are not significant ($p > \alpha$) and that the composting system was reproducible.

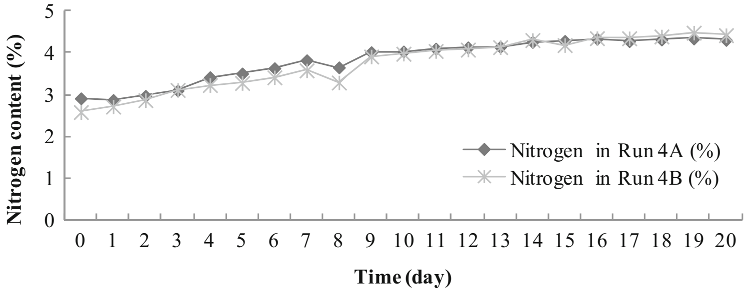
General parameters of composting process

The temporal variations of general parameters of the eight runs followed the typical patterns of aerobic composting reactions. The changes of temperature levels of the eight runs are shown in Fig. 4a. Rapid heat-generating processes were observed in all of the eight runs. The temperature in runs 2 to 6 stayed at thermophilic level (higher than 45 °C) for more than 6 days, and the composting period lasted for 21 days. The temperature in runs 1 and 7 stayed in mesophilic stage (20 to 45 °C) for about 20 days before it raised up to thermophilic level, while that in run 8 did not reach thermophilic level but stayed in the mesophilic stage for around 30 days. During the mesophilic period, microbial activities were relatively low, leading to an extended duration for composting process of runs 1, 7, and 8, which lasted for 33, 39, and 34 days, respectively. The

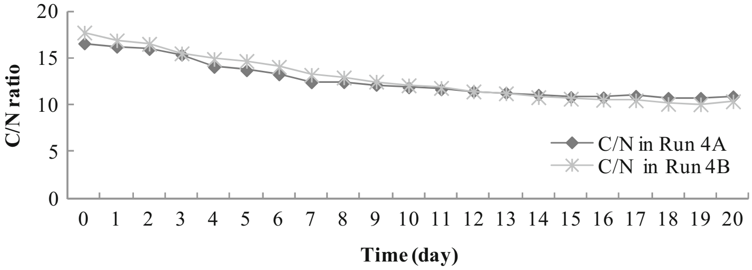
Fig. 3 Temporal variations of **a** carbon content, **b** nitrogen content, and **c** C/N ratio in runs 4A and 4B



a) Temporal variations of carbon content



b) Temporal variations of nitrogen content



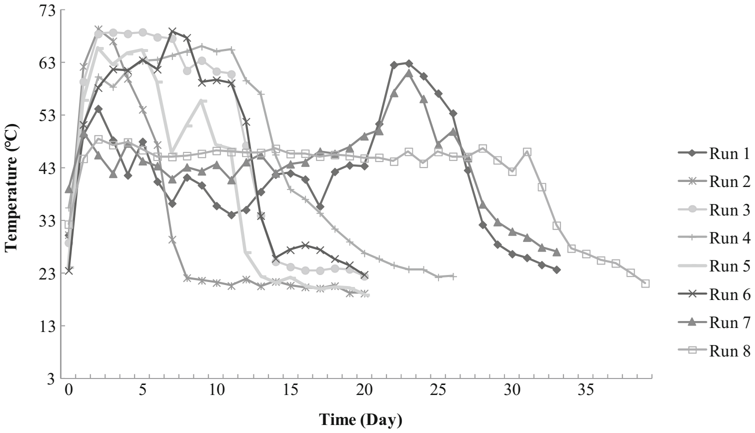
c) Temporal variations of C/N ratio

starting culture amounts in the three runs with extended composting duration were all relatively low (only 5 %). This implies that the composting processes were influenced by the associated process inhibition resulted from

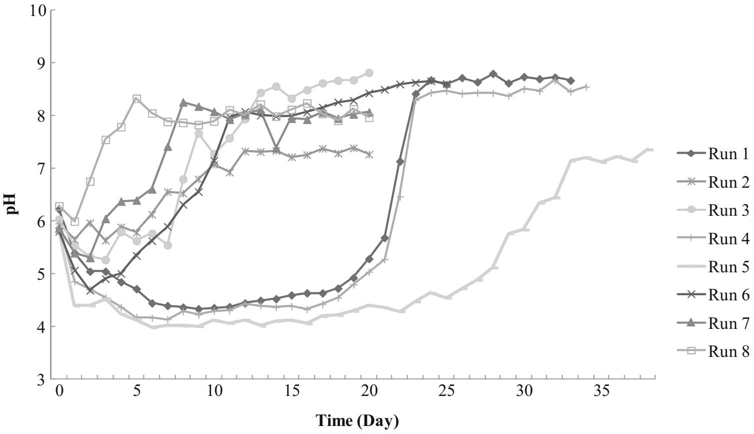
Table 3 Analysis of variance for runs 4A and 4B (α=0.05)

	Source of variance	Degree of freedom	Sum of squares (SS)	Mean square (MS)	F_0	*P* value
Carbon contents	Run	1	3.12	3.12	1.94	0.171
	Error	40	64.23	1.61		
	Total	41	67.34			
Nitrogen contents	Run	1	0.07	0.07	0.22	0.639
	Error	40	12.80	0.32		
	Total	41	12.87			
C/N ratio	Run	1	0.40	0.40	0.08	0.774
	Error	40	194.23	4.86		
	Total	41	194.64			

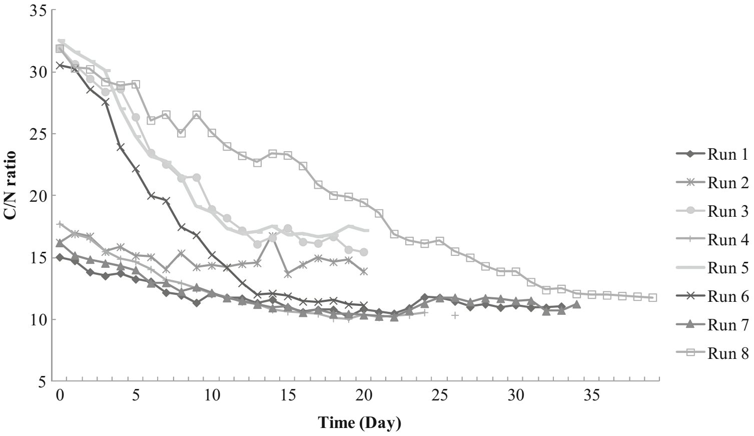
Fig. 4 Temporal variations of general parameter ratio for the eight runs. **a** Temporal variations of temperature. **b** Temporal variations of pH. **c** Temporal variations of C/N ratio



a) Temporal variations of temperature



b) Temporal variations of pH



c) Temporal variations of C/N ratio

low starting culture amount. Temporal variations of pH in the eight runs are presented in Fig. 4b. Starting from the second and third days, the pH in runs 2 to 6 slowly increased and eventually remained at 7.3 to 8.6 till the ends of the processes, whereas pH in runs 1, 7, and 8 kept dropping and stayed at a relatively low level till

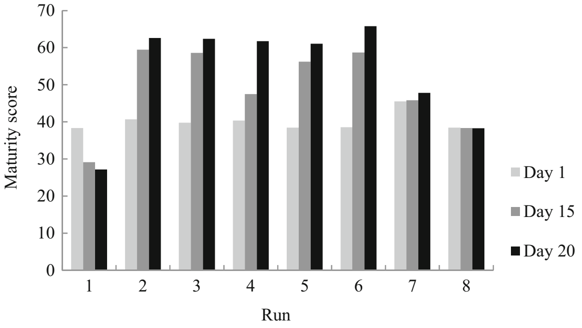


Fig. 5 Maturity on days 1, 15, and 20 for the eight runs

they started increasing after over 10 days. The significant difference between the pattern of runs 2 to 6 and that of runs 1, 7, and 8 in terms of pH variations also implies the influences of starting culture amount. Temporal variations of C/N in the eight runs are shown in Fig. 4c. Although the initial C/N was different (as discussed in the experiment design), the C/N ratio exhibits a general decreasing trend of C/N ratio in all of the eight experiment runs. The C/N ratio dropped because of the loss of carbon mainly as carbon dioxide. As the decomposition processed, carbon content of the composting material decreased with time (Goyal et al. 2005). In runs 3, 5, 6, and 8, where the initial C/N was higher than 30, there were sharp decays in the C/N ratio at the beginning of the composting process. On one hand, it is due to the carbon loss as the decomposition processed; on the other hand, a high C/N ratio might cause the composting system to become nitrogen-limited, lead to nitrogen immobilization, and thus result in a decrease of the C/N ratio (Sikora 1999). The similar significant negative correlation between the initial C/N ratio and the nitrogen loss was also found in the previous studies (Michel Jr et al. 2004).

Compost maturity evaluation

The compost maturity was assessed based on the maturity indicators using the proposed fuzzy inference system. According to the discussion of general parameter changes in the eight runs, the composts in runs 2 to 6 reached composting maturation on day 20. Figure 5 shows the maturity on days 1, 15, and 20 for the eight runs, which represent the initial, middle, and final phases of the composting process in runs 2 to 6, respectively. The maturity values in runs 2 to 6 show significant increases over the composting duration, which has an agreement with the typical patterns of composting and proves that the developed fuzzy inference system has very good ability in evaluating the compost maturity. The trends of maturity evolution in runs 1, 7, and 8 show different patterns from those in runs 2 to 6. This could be explained by the extended composting processes. The period of days 1 to 20 was the initial phase for these three runs, and it is acceptable that the maturity was not stable. Even though the maturity of runs 1, 7, and 8 fluctuated in the studied period, it is obvious that the averages of maturity scores of these three runs are relatively low. When the composting evolution in runs 2 to 6 was completed with the maturity above 60 on day 20, the maturity in runs 1, 7, and 8 were below 40. This is because the composting periods of runs 2 to 6 were shorter than those of runs 1, 7, and 8. As shown in Fig. 4a, runs 2 to 6 all reached or almost reached the ambient temperature on day 20, which implies that most of the easily degradable organic substances had been consumed and the composting periods were over. While the composting processes took only approximately 20 days in runs 2 to 6, the processes of runs 1, 7, and 8 lasted much longer. Temperature in runs 1, 7, and 8

Table 4 Contrast constants for the 2^{4-1} factorial design

Treatment	*A*	*B*	*C*	*D*	Maturity (day 15)	Maturity (day 16)	Maturity (day 17)	Maturity (day 18)	Maturity (day 19)	Maturity (day 20)
1	−1	−1	−1	−1	29.12	30.45	34.35	34.86	35.14	27.17
bc	−1	1	1	−1	59.46	59.93	57.78	61.27	58.66	62.59
ac	1	−1	1	−1	58.56	60.74	61.06	61.08	60.28	62.40
cd	−1	−1	1	1	47.51	46.53	54.13	58.57	61.41	61.73
abcd	1	1	1	1	56.25	59.73	62.81	62.45	62.64	61.04
ab	1	1	−1	−1	58.63	60.01	61.30	61.74	62.27	65.78
bd	−1	1	−1	1	45.82	45.55	46.91	45.38	47.00	47.85
ad	1	−1	−1	1	38.33	38.18	38.02	38.71	38.77	38.28

Table 5 Factor effect estimates and sums of squares for maturity on days 15 to 20

Factor effect estimates and sums of squares for maturity on days 15 to 17

Model term	Day 15				Day 16				Day 17			
	Contrasts	Effect estimate	Sums of squares (SSs)	Percent contribution	Contrasts	Effect estimate	Sums of squares (SSs)	Percent contribution	Contrasts	Effect estimate	Sums of squares (SSs)	Percent contribution
A	29.86	7.47	111.47	12.85	36.20	9.05	163.82	17.02	30.02	7.51	112.66	13.16
B	46.64	11.66	271.86	31.34	49.33	12.33	304.13	31.59	41.24	10.31	212.63	24.83
C	49.89	12.47	311.12	35.87	52.74	13.18	347.68	36.12	55.19	13.80	380.74	44.47
D=*ABC*	−17.87	−4.47	39.91	4.60	−21.14	−5.28	55.86	5.80	−12.62	−3.16	19.92	2.33
AB (*CD*)	−10.66	−2.67	14.21	1.64	−7.68	−1.92	7.38	0.77	8.83	2.21	9.75	1.14
AC (*BD*)	−14.19	−3.55	25.16	2.90	−8.17	−2.04	8.35	0.87	−6.10	−1.53	4.65	0.54
AD (*BC*)	−27.37	−6.84	93.62	10.79	−24.56	−6.14	75.40	7.83	−30.45	−7.61	115.88	13.53
Average	196.47	49.21	–		199.82	50.14	–		166.80	52.04	–	

Factor effect estimates and sums of squares for maturity on days 18 to 20

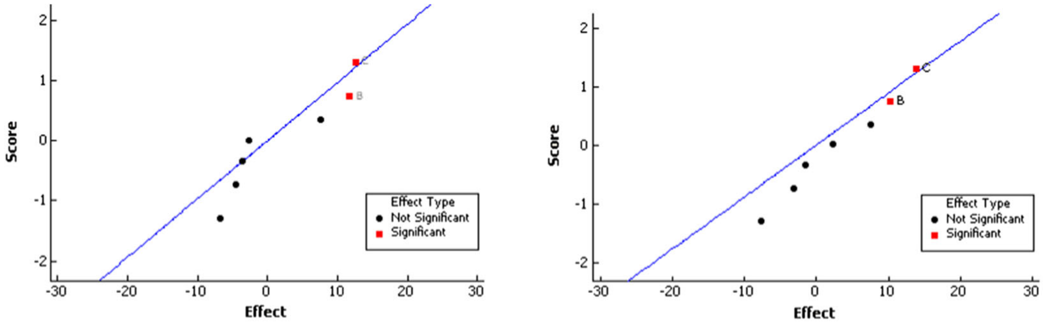
Model term	Day 18				Day 19				Day 20			
	Contrasts	Effect estimate	Sums of squares (SS)	Percent contribution	Contrasts	Effect estimate	Sums of squares (SS)	Percent contribution	Contrasts	Effect estimate	Sums of squares (SS)	Percent contribution
A	23.91	5.98	71.45	7.75	21.76	5.44	59.18	6.64	28.16	7.04	99.16	7.11
B	37.62	9.40	176.87	19.19	34.97	8.74	152.86	17.15	47.68	11.92	284.21	20.39
C	62.67	15.67	490.96	53.27	59.81	14.95	447.09	50.15	68.67	17.17	589.51	42.29
D=*ABC*	−13.84	−3.46	23.95	2.60	−6.53	−1.63	5.34	0.60	−9.05	−2.26	10.25	0.74
AB (*CD*)	11.18	2.80	15.63	1.70	16.75	4.19	35.06	3.93	4.59	1.15	2.64	0.19
AC (*BD*)	−16.52	−4.13	34.11	3.70	−16.06	−4.01	32.23	3.61	−29.91	−7.48	111.83	8.02
AD (*BC*)	−29.48	−7.37	108.60	11.78	−35.76	−8.94	159.81	17.92	−48.68	−12.17	296.28	21.26
Average	172.85	53.01	–		158.13	53.27	–		227.58	53.36	–	

stayed in mesophilic stage (20 to 45 °C) for over 20 days and reached their peaks on the 22nd or 23rd day while the pH was drastically increasing, which indicates that the maturation was still in process. The composting durations lasted 33, 34, and 39 days for runs 1, 7, and 8, respectively. This is the reason that the maturity scores were low on the 20th day as shown in Fig. 5.

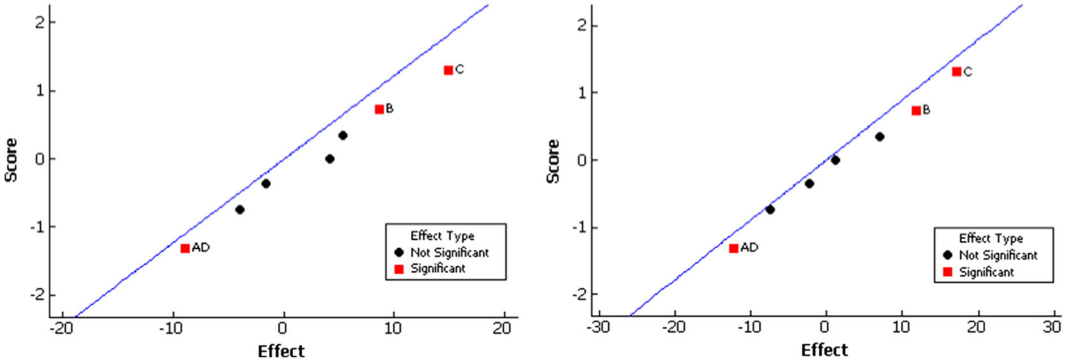
Effects analysis

According to the experimental design illustrated above, factors *A*, *B*, *C*, and *D* represent C/N ratio, aeration rate, starting culture amount, and coal ash amendment, respectively. The plus and minus signs as well as maturity scores for the contrast constants of the 2^{4-1} fractional factorial design are shown in Table 4. According to these contrasts, the factor effect estimates and SS for maturity on days 15 to 20 were calculated (Table 5). The effect estimate results show that factors *C* (starting culture amount) and *B* (aeration rate) are the two factors that had the largest percent contribution to the maturity. The percent contribution of starting culture amount accounted for over 30 % for the maturity on days 15 and 16, and it was over 40 % for the maturity on days 17 to 20. The percent contribution of aeration rate accounted for 17.15 to 31.59 % for the maturity on days 15 to 20. The percent contribution of the interaction of factors *A* and *D* was relative high in the last 3 days. Normal probability plots of the effect estimates were constructed as shown in Fig. 6. The normal probability plots show the same results as the effect estimate calculation. An application of Ockham's razor, a scientific principle that states that when one is confronted with several different possible interpretations of a phenomena, the simplest interpretation is usually the correct one (Montgomery 2001). In this case, the effects of individual factors *B* and *C* are simpler and more significant than the interaction effect of *A* and *D*. Therefore, it is concluded that the effects of starting culture amount and aeration rate have more significant effects on compost maturity than those of C/N ratio and amendment, or any of the interactions.

The significance of starting culture amounts can be found not only on the maturity, but also in the temporal variations of pH and temperature in the eight runs as mentioned above. Starting culture is used as seeding and bulking agents during waste composting (Namkoong



a) Normal probability plots of the effects for maturity on Day 15 b) Normal probability plots of the effects for maturity Day 17



c) Normal probability plots of the effects for maturity Day 19 d) Normal probability plots of the effects for maturity Day 20

Fig. 6 Normal probability plots of the effects for maturity. **a** Day 15. **b** Day 17. **c** Day 19. **d** Day 20 et al. 1999). It could provide diversified microbial species that could help accelerate the start-up process (Nakasaki and Akiyama 1988). It could also serve as a chemical pH buffer, reducing the inhibitory effects of the organic acids (Sundberg and Jöson 2005). Moreover, it could dilute the fresh waste, decreasing the readily available energy per volume. Thus, the risk of high-odor and inhibiting organic acid concentrations (resulting from partial oxygen depletion caused by rapid degradation of easily degradable matters) could be reduced. Therefore, starting culture has several stabilizing effects on the composting process, and introducing an adequate amount of matured compost to the food waste composting system could help avoid the initial period and shorten the maturation duration.

The effects of aeration rate could be explained by its importance in bringing oxygen. Aeration is a control variable used to regulate composting processes for achieving desirable performance. Aeration rate could provide oxygen for the microorganisms to aerobically decompose the substrate, and it can remove heat from the composting materials in order to maintain the temperature levels. Therefore, aeration rate could affect the temperature levels and oxygen concentrations in the compost reactions and thus influence the maturity of the compost products.

Conclusion

In this study, the effects of C/N ratio, aeration rate, starting culture amount, and coal ash amendment on the compost maturity in food waste composting were studied. A 2^{4-1} fractional factorial design method combined with well-controlled experiments was used to analyze the effects of these system factors. The compost maturity was synthetically evaluated by developing a Mamdani fuzzy rule-based inference system. TI, O_2 uptake rate, ammonium, OM loss, C/N ratio, and ash content were chosen as indicators of the multi-criterion maturity evaluation. Weights of these indicators were assigned using the eigenvalue scaling method in a hierarchical structure. Maturity evaluation results of the eight runs demonstrated that this fuzzy synthetic evaluation method has very good ability to evaluate the compost maturity in food waste composting. The effect analysis results demonstrated that starting culture amount is the factor that contributes most to the product maturity in composting process. Starting culture could provide a chemical pH buffer, reducing the inhibitory effects of the organic acids, and affects the whole composting process and thus the compost maturity. Aeration rate was found as the second important factor to compost maturity, due to its influence on the oxygen content and temperature in the composting reaction. The results can provide decision support for the process management of food waste composting. It has been demonstrated that composting with the optimal initial starting culture and aeration rate could significantly improve the compost maturity and thus result in better compost product quality. The proposed fuzzy rule-based inference system and fractional factorial design for maturity evaluation can be extended to other composting systems to help conduct best management practices of composting.

Acknowledgments This research was supported by the Natural Sciences and Engineering Research Council of Canada, the Program for Innovative Research Team in University (IRT1127), and the 111 Project (B14008).

References

Andrews, S. S., & Carroll, C. R. (2001). Designing a soil quality assessment tool for sustainable agroecosystem management. *Ecological Applications, 11*(6), 1573–1585.

Araujo, A. S. F., Miranda, A. R. L., et al. (2015). Soil microbial properties after 5 years of consecutive amendment with composted tannery sludge. *Environmental Monitoring and Assessment, 187*(1), 1–7.

Beck-Friis, B., Pell, M., et al. (2000). Formation and emission of N2O and CH4 from compost heaps of organic household waste. *Environmental Monitoring and Assessment, 62*(3), 317–331.

Bernal, M. P., Paredes, C., et al. (1998). Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Bioresource Technology, 63*(1), 91–100.

Box, G. E. P., Hunter, J. S., et al. (1978). *Statistics for experimenters: an introduction to design, data analysis, and model building*. New York: Wiley.

Cabala, P. (2010). Using the analytic hierarchy process in evaluating decision alternatives. *Operations Research and Decisions, 1*, 1–23.

Cherkassky, V. (1998). Fuzzy inference systems: a critical review. *Computational Intelligence: Soft Computing and Fuzzy-Neuro Integration with Applications*, Springer. 177–197.

Daniel, C. (1959). Use of half-normal plots in interpreting factorial two-level experiments. *Technometrics, 1*(4), 311–341.

de Bertoldi, M., Rutili, A., et al. (1988). Composting management: a new process control through O2 feedback. *Waste Management & Research, 6*(3), 239–259.

Fries, A., & Hunter, W. G. (1980). Minimum aberration 2 k-p designs. *Technometrics, 22*(4), 601–608.

Fu, Z. Y. (2004). A Fuzzy inference system for synthetic evaluation of compost maturity and stability Master of Engineering University of Regina.

Getahun, T., Gebrehiwot, M., et al. (2014). The potential of biogas production from municipal solid waste in a tropical climate. *Environmental Monitoring and Assessment, 186*(7), 4637–4646.

Goyal, S., Dhull, S., et al. (2005). Chemical and biological changes during composting of different organic wastes and assessment of compost maturity. *Bioresource Technology, 96*(14), 1584–1591.

Gunalay, Y., Yeomans, J., et al. (2012). Modelling to generate alternative policies in highly uncertain environments: an application to municipal solid waste management planning. *Journal of Environmental Informatics, 19*(2), 58–69.

Gunst, R. F., & Mason, R. L. (2009). Fractional factorial design. *Wiley Interdisciplinary Reviews: Computational Statistics, 1*(2), 234–244.

Humer, M., & Lechner, P. (1999). Alternative approach to the elimination of greenhouse gases from old landfills. *Waste Management and Research, 17*(6), 443–452.

Komine, N., Shiiba, K., et al. (2004). A proposal for quality evaluation of animal-waste compost by statistic analysis (part 2). *Journal-Japanese Society of Agricultural Machinery, 66*(2), 55–60.

Leiva, M. T. G., Casacuberta, A. A., et al. (2003). Application of experimental design technique to the optimization of bench-scale composting conditions of municipal raw sludge. *Compost Science & Utilization, 11*(4), 321–329.

Li, Y., Huang, G., et al. (2008). A simulation-aided factorial analysis approach for characterizing interactive effects of system factors on composting processes. *Science of the Total Environment, 402*(2), 268–277.

Li, W., Huang, G., et al. (2013a). An inexact fuzzy programming approach for power coal blending. *Journal of Environmental Informatics, 21*(2), 112–118.

Li, Z., Huang, G., et al. (2013b). Inexact two-stage stochastic credibility constrained programming for water quality management. *Resources, Conservation and Recycling, 73*, 122–132.

Lv, Y., Huang, G., et al. (2010). Planning regional water resources system using an interval fuzzy bi-level programming method. *Journal of Environmental Informatics, 16*(2), 43–56.

Mamdani, E. H., & Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies, 7*(1), 1–13.

Miao, D., Huang, W., et al. (2014). Planning water resources systems under uncertainty using an interval-fuzzy de novo programming method. *Journal of Environmental Informatics, 24*(1), 11–23.

Michel, F. C., Jr., Pecchia, J. A., et al. (2004). Mass and nutrient losses during the composting of dairy manure amended with sawdust or straw. *Compost Science & Utilization, 12*(4), 323–334.

Montgomery, D. C. (2001). *Design and analysis of experiments* (5th ed.). New York: Wiley.

Montgomery, D. C. (2008). *Design and analysis of experiments*. New York: John Wiley & Sons.

Nair, J., Sekiozoic, V., et al. (2006). Effect of pre-composting on vermicomposting of kitchen waste. *Bioresource Technology, 97*(16), 2091–2095.

Nakasaki, K., & Akiyama, T. (1988). Effects of seeding on thermophilic composting of household organic waste. *Journal of Fermentation Technology, 66*(1), 37–42.

Nakasaki, K., Yaguchi, H., et al. (1993). Effects of pH control on composting of garbage. *Waste Management & Research, 11*(2), 117–125.

Namkoong, W., Hwang, E. Y., et al. (1999). A comparative evaluation of maturity parameters for food waste composting. *Compost Science & Utilization, 7*(2), 55–62.

Pisa, C., & Wuta, M. (2013). Evaluation of composting performance of mixtures of chicken blood and maize stover in Harare, Zimbabwe. *International Journal Of Recycling of Organic Waste in Agriculture, 2*(1), 1–11.

Quirós, R., Villalba, G., et al. (2014). Environmental assessment of two home composts with high and low gaseous emissions of the composting process. *Resources, Conservation and Recycling, 90*, 9–20.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15*(3), 234–281.

Saha, J., Panwar, N., et al. (2013). Effect of methods of preparation on distribution of heavy metals in different size fractions of municipal solid waste composts. *Environmental Monitoring and Assessment, 185*(11), 8815–8821.

Senthil Kumar, D., Satheesh Kumar, P., et al. (2014). Evaluation of vermicompost maturity using scanning electron microscopy and paper chromatography analysis. *Journal of Agricultural and Food Chemistry, 62*(13), 2738–2741.

Sikora, L. J. (1999). MSW compost reduces nitrogen volatilization during dairy manure composting. *Compost Science & Utilization, 7*(4), 34–41.

Smårs, S., Gustafsson, L., et al. (2002). Improvement of the composting time for household waste during an initial low pH phase by mesophilic temperature control. *Bioresource Technology, 84*(3), 237–241.

Sun, X. L. (2006). Nitrogen transformation in food-waste composting. Master of Applied Science University of Regina.

Sundberg, C., & Jöson, H. (2005). Process inhibition due to organic acids in fed-batch composting of food waste influence of starting culture. *Biodegradation, 16*(3), 205–213.

Tognetti, C., Mazzarino, M., et al. (2007). Improving the quality of municipal organic waste compost. *Bioresource Technology, 98*(5), 1067–1076.

Wang, J. H., Lu, X. G., et al. (2009). Fuzzy synthetic evaluation of wetland soil quality degradation: a case study on the Sanjiang Plain, Northeast China. *Pedosphere, 19*(6), 756–764.

Xiao, Y., Bai, X., et al. (2007). The composition, trend and impact of urban solid waste in Beijing. *Environmental Monitoring and Assessment, 135*(1–3), 21–30.

Xu, Y., Huang, G., et al. (2014). A two-stage fuzzy chance-constrained model for solid waste allocation planning. *Journal of Environmental Informatics, 24*(2), 101–110.

Yu, H., & Huang, G. H. (2009). Effects of sodium acetate as a pH control amendment on the composting of food waste. *Bioresource Technology, 100*(6), 2005–2011.

Yu, H., Huang, G. H., et al. (2010). Inhibitory effects of organic acids on bacteria growth during food waste composting. *Compost Science & Utilization, 18*(1), 55–63.

Zhang, Y., Huang, G., et al. (2008). Quality evaluation for composting products through fuzzy latent component analysis. *Resources, Conservation and Recycling, 52*(10), 1132–1140.

Zhang, Y., Luo, W., et al. (2014). Effects of pig manure containing copper and zinc on microbial community assessed via phospholipids in soils. *Environmental Monitoring and Assessment, 186*(8), 5297–5306.

Zhou, Y., Huang, G. H., et al. (2013). Water resources management under multi-parameter interactions: a factorial multi-stage stochastic programming approach. *Omega, 41*(3), 559–573.