Performance of in-vessel composting of food waste in the presence of coal ash and uric acid

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ABSTRACT

Massive quantities of food waste often coexist with other agroindustrial and industrial waste, which might contain coal ash (CA) and uric acid (UA). This study investigated the influence of CA and UA on the composting of food waste in the in-vessel system. The patterns of food waste composting were compared among various combinations. The results showed that the temperature level was enhanced in the presence of CA and UA during the first 8 days. The significant drop in pH was observed in the treatment without any amendment. But the presence of CA could alleviate the drop of pH. More intensive organic mass reduction took place in the treatments with amended CA and UA in the first half of process. The O_2 uptake rate in the reactor with CA and UA was higher than that with only CA in the early stage. Both thermophilic and mesophilic microorganisms were present throughout the composting period. The populations of both thermophilic and mesophilic microorganisms were influenced when amended with CA and UA. The decreasing trend in C/N ratio was shown in all the reactors, while a relatively lower C/N ratio was obtained in the series with both CA and UA.

1. Introduction

With the rapid development of economy and population, a large amount of solid waste has been generated from domestic, industrial and agricultural activities over the last few decades [1,2]. Food waste, which can be from various sources such as restaurants, markets, residents and many other food-processing facilities, is one of the most general forms of organic solid waste [3]. In some areas of China and Korea, it can account for approximately more than one quarter of the total solid waste generation [4,5]. Food waste has been demonstrated to be a threat to human health due to the potentially releasing of nuisance odors and leachate. Inappropriate disposal practice has often resulted in various economic, environmental and biological losses across the world.

Composting has been developed as one of the most promising solid waste disposal methods for safe treatment strategies [6–8]. During the composting process, the microorganisms decompose the substrate through breaking it down from complex to simpler compounds under aerobic conditions [9,10]. Composting can significantly reduce waste volume within various composting systems, such as non-reactor, enclosed reactor and in-vessel systems [11]. The produced product with humus-like property can be used for

stimulating microbial activities and plant growth in various field applications. From the viewpoint of green-recycling in the ecosystem, composting is an environmentally and economically sound manner.

The properties of different solid wastes can be quite variable and this variability could play an important role in the effectiveness of composting. To facilitate the treatment process, pre-separation of organic wastes at source is becoming a more common practice in several European countries [12]. However, it is difficult to achieve such routine classification for many areas due to high cost of operating and maintaining. Massive quantities of food waste often coexist with other agroindustrial and industrial waste. The challenge is especially poignant in many developing countries. Some researches on food waste composting have been reported before, particularly on aspects relating to degradation in simple compost cultures [9,13], investigations on food waste composting in complex multi-source mixtures are relatively limited in scope. To better understand the composting mechanism within real-world applications, there is a need to investigate the interactions among diverse types of materials for the food waste treatment.

Coal ash (CA) is the major waste produced by the burning of coal in large quantities by electricity-generating power plants [14]. The global amount of CA from coal combustion has been estimated to be 500 million tonnes per year [15]. Some CA can be used in cement products, road bases and structural fill; however, more than 70% of

the CA is dumped into landfills as waste [16]. Recently, there have been several reports about the influence of CA on composting. The high porosity and alkali metal oxides in CA might improve the quality of composting substrate. Belyaeva and Haynes [17] have proved the feasibility of co-composting municipal green waste with additional CA to produce manufactured soil material. They also find the amendment of CA could increase the water holding capacity of the substrate. Koivula et al. [18] studied the behavior of the organic carbon during the composting of source-separated catering waste mixed with CA. The results showed that the CA could increase the rate of mineralization of compost and the formation of humic acids. The quality of compost prepared from coal ash and crop residue have also been assessed by Gaind and Gaur [19] and their study showed the compatibility of CA with the microbes. But few efforts have been made to examine the composting of food waste and CA under complicated conditions. As another common solid waste, manure often contains uric acid (UA) as an important bicyclic heterocyclic purine derivative. UA can account for 70% of the total N components in poultry feces and this proportion is influenced by animal diet [20]. Available N supplied from UA could potentially facilitate the microbial activities during the composting. In several previous studies, co-composting of manure and other substrates has also been demonstrated under aerobic conditions. The co-composting of solid swine manure and pine sawdust has been investigated in forced-aeration composting systems [21]. The biological and thermal kinetics of the process has also been analyzed during the composting of dairy manure and tomato plant residues [22]. However, very few studies have been conducted to investigate the composting of manure and food waste, despite the prevalence of composting technique. The potential influences and roles of many manure constituents are still not well understood. The coexistence of food waste with agricultural and industrial wastes may be ubiquitous in many areas. Although the study of multi-component waste composting is of great economic and environmental importance, the complexity of their composition makes related study difficult due to the great variety of raw substances. The study in food waste composting in the presence of other components will be helpful for better understanding of this treatment process.

For the experiment of this study, we will evaluate the performance of food waste composting in the presence of CA and UA. Tests will be conducted in the in-vessel composting system. The patterns of food waste composting are compared among various combinations to investigate the influences of CA and UA. The variations of temperature, pH, organic mass reduction rate, O_2 consumption, microbial population and C/N ratio are studied. The results of this study will have important implications for developing appropriate treatment of food waste by composting.

2. Material and methods

2.1. Composted wastes

To investigate the performance of food waste composting in the presence of CA and UA, three experimental treatments were carried out using in-vessel composting reactors. The composite raw materials could offer an advantage to be duplicated from batch to batch allowing ready comparisons among various tests [23]. The composite food waste mixture including potatoes, carrots, steamed rice, meat and leaves was used as the composting raw material. All the raw materials were obtained from a local grocery store. They were minced into pieces with diameter less than 5 mm using food processor and mixed well before the composting reaction began. For Run B and Run C, 4 kg of CA were added to the compost mixture, respectively. The CA was obtained from the

Table 1
Composition of raw composting materials.

Component	Run A	Run B	Run C
Potato (kg)	1.7	1.7	1.7
Carrot (kg)	2.7	2.7	2.7
Steamed rice (kg)	2.8	2.8	2.8
Meat (kg)	0.5	0.5	0.5
Leaves (kg)	0.6	0.6	0.6
Starting culture (kg)	0.5	0.5	0.5
Coal ash (kg)	0	4	4
Uric acid (g)	0	0	84

Boundary Dam Power Station, which is a coal fired station owned by SaskPower, located near Estevan, Saskatchewan, Canada. For Run C, 84 g of UA ($C_5H_4N_4O_3$, Sigma–Aldrich, MO, USA) were added to the compost mixture. Run A was conducted as a control treatment without CA and UA addition. For each run, a parallel run was conducted simultaneously. The detailed composition of raw materials for the compositing processes is shown in Table 1. The values are the wet weight data of the components. The characteristics of the composite food waste are shown in Table 2.

2.2. In-vessel composting system

A schematic diagram of the in-vessel composting system in present study is illustrated in Fig. 1. The cylindrical composting reactor was of acrylic column, with a working volume of 30 L and dimensions of 300 mm × 450 mm × 6 mm (diameter × depth × thickness). To prevent conductive and reflecting heat loss, heavy-duty aluminum foil, foam and fibreglass were employed as three layers of heat-insulating materials, respectively. Two thermometers (Traceable 15-077-9E; Control Company, TX, USA) were used to monitor temperature variation. The upper thermometer located in the middle of the reactor, while the lower one was placed 1 in. above the segmentation plate. The system was aerated by vacuum pump (MOA-P101-AA; GAST Manufacturing Inc., MI, USA). Air was evenly distributed to the waste mixture through a perforated plate at a flow rate of 0.1 vvm (volume of aeration/working volume of reactor/minute). The exhaust gas from the reactor passed through a condensate trap and was discharged to the laboratory ventilation system after analysis.

2.3. Composting procedure

The composting reactors were run in a laboratory with the ambient temperature at 20 ± 1 °C. The reactors were opened once daily for weighing, turning, observation, and sampling. Before each sampling, the materials in the reactors were stirred well with a shovel to homogenize the mixture. Samples were subsequently taken from different levels of the central reactors. After mixing, subsamples of approximately 50 g were used for the further analysis. For each analysis, three replicates were conducted.

Table 2
Characteristics of the composite food waste.

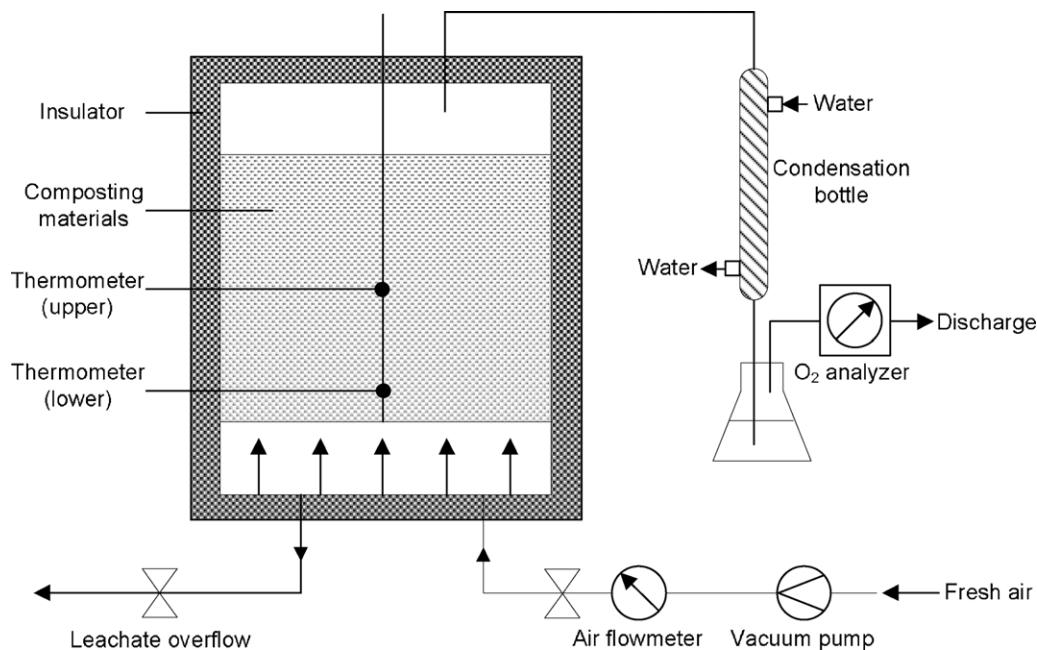| Parameters	Food waste
pH	5.79
Moisture content (%)	62.35
Ash content (%)	1.74
Organic content (%)	35.91
Carbon (%)	45.12
Nitrogen (%)	1.39
C/N ratio	32.46

Fig. 1. Schematic diagram of the composting system.

2.4. Analytical methods

Dry weight was determined after drying at 105 °C overnight. Organic matter content was quantified by heating samples at 550 °C for 4 h. The pH level was measured by a benchtop pH/temperature meter (410A Plus; Thermo Orion, MA, USA) in solution of 5 g compost and 10 mL deionized water. Oxygen in the exhaust gas was tested using an M40 multi-gas monitor (Industrial Scientific Corp., PA, USA). The total carbon (C) and nitrogen (N) contents in the compost were determined by the LECO TruSpec CN determinator (LECO Corporation, MI, USA). A solid sample was acidified by pouring 3 mL 0.1 M H_2SO_4 over the entire sample before drying to avoid ammonium losses, and the dry sample was then ground to a homogeneous powder for analysis. Microbial enumeration was determined using the spread plate counting method [24]. The incubation media was 10% tryptic soy broth agar. For each test, 10 g (fresh weight) of compost sample was added into a 250 mL Erlenmeyer flask with 90 mL of 0.85% sterile sodium chloride solution. The flask was capped and placed on a reciprocal shaker at 20 ± 1 °C and 200 rpm for 30 min. Then certain amount of supernatant was transferred, and diluted it with 0.85% sterilized sodium chloride solution to prepare tenfold serial dilution. The dilution was set to a range from 10^{-2} to 10^{-10}. Four series of dilution where the microorganism can be adequately characterized were selected. 0.1 mL of each series was drawn and spread to a Petri plate containing the required medium. Plates were incubated at 25.0 °C for 7 days to enumerate total mesophilic microorganisms and at 55.0 °C for 2 days to enumerate total thermophilic microorganisms. The unit of microbial populations was colony forming unit (CFU)/g sample in logarithm scale.

2.5. Statistical analyses

Statistical analyses were performed with the use of the Minitab (Minitab Inc., PA, USA) statistical software package. The mean and standard deviation of the tree replicates were reported for all measured parameters. ANOVA and Tukey test were applied to compare differences among means of different treatments. The differences between any pair of treatment means were tested using the least significant difference test with α-value (significance level) at 5%.

3. Results and discussion

3.1. Temperature and pH profiles

The profile of temperature is shown in Fig. 2a. In all the reactors, the temperature increased quickly during the first several days. Run B could reach 62.4 °C within 2 days. The temperature variation of Run C also showed a similar pattern at this stage. But the temperature of Run C was significantly higher that of Run B ($p < 0.05$) during the first 3 days. Although Run A also showed an increasing temperature in the initial stage, the temperature level was lower than that observed in Run B and Run C. The rapid increase of reaction temperature during the early stage was mainly due to the microbiological metabolism. Easily biodegradable fractions in food waste such as sugars, proteins and amino acids were present in this stage. Suitable bacteria and fungi could degrade these simple compounds and generate heat. Similar high temperature has been often observed during composting of organic wastes, especially for easily degraded and energy-rich materials like household waste [1].

During the following experimental period, the temperature of Run B and Run C remained at a high level for several days. Then the temperature of Run B began to decrease after day 11, while the temperature of Run C began to decrease after day 10. The temperature of Run A fluctuated around 45 °C. At day 23, the temperature of Run A, Run B and Run C were 46.3, 23.8 and 21.4 °C, respectively. The high temperature range observed in present study is close to the range for thermophilic bacteria and fungi to colonize and degrade the substrate [25]. A temperature above 55 °C could ensure the destruction of pathogenic organisms within a compost pile, which can create favorable conditions for further application [1]. The later drop off of the temperature reflected the depletion of readily biodegradable components. In the case of both Run B and Run C, there was a mesophilic phase (up to 45 °C) before the temperature decreased spontaneously to ambient temperature for both Run B and Run C. But the short mesophilic period was shown
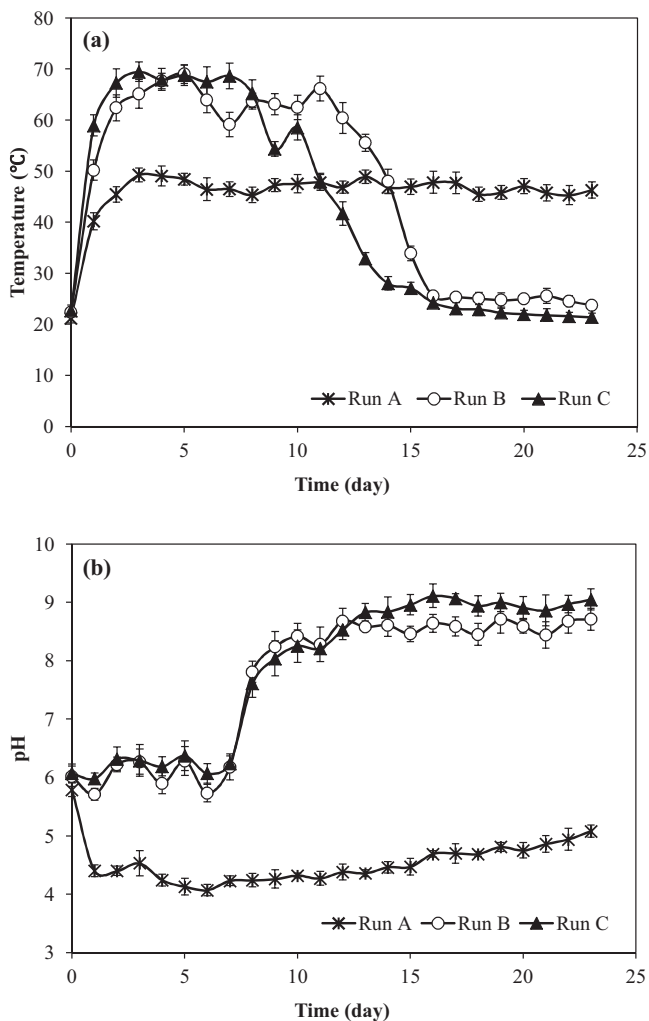
Fig. 2. Temperature and pH profiles during the composting process.

was slightly higher in Run B and Run C. This was due to the enhanced alkalinity by the amendment of CA. But there was no significant difference for the pH level between Run B and Run C. Addition of UA did not further increase the initial pH of the composting mixture.

In the beginning, the pH in Run A decreased and reached a minimum of 4.07 at day 6. The significant drop in pH for treatment without any amendment may be due to the formation of carbon dioxide and organic acids [29]. The abundant organic components and microbiological activities within food waste compost could lead to the generation of secondary acidic metabolites, which make a significant contribution to lowering the pH. Similar acidic environment has also been observed in previous studies about composting [13,30]. By contrast, a significant decrease of pH was not observed in Run B. The pH of Run B fluctuated from 5.71 to 6.18 from day 1 to day 7. The alkaline components such as alkali metal oxides in CA could buffer the acidity of the composting mixture in this stage. A slightly higher pH level was shown in Run C during this stage, which was due to the addition of UA in food waste. It has been also noted the sequential addition of urea could lead to alkalinization [31]. Breakdown of UA and undigested protein in the mixture could all contribute to the increased pH.

As the process proceeds, the compost pH of Run A increased slowly. In comparison, both of Run B and Run C were undertaking a rapid increase of pH after day 7. But the increasing trend became less significant at a later stage. There was no significant difference ($p > 0.05$) between the pH values in Run B and Run C from day 6 to day 11; however, the pH of Run C was significantly higher that of Run B ($p < 0.05$) after day 13.

At the end of composting, the pH values for Run B and Run C were 8.71 and 9.05, respectively. The decomposition of proteins, ammonification, and elimination of the carbon dioxide can all contribute to the pH increase [26,32]. But the high level of pH observed during the final stage might pose potential risk for ammonia emission. The slightly higher pH in Run C might be due to the faster decomposition of substrate and breakdown of UA in the UA-amended reactor. In contrast, when the sewage sludge was amended with coal fly ash in a previous study, it was observed the pH could increase as time went on, but followed by a drop of pH later [33]. Such difference is perhaps ascribed to the different CA dosage and composting substrate properties.

3.2. Organic matter reduction during composting

The extent of organic matter reduction is calculated from the degradation percentage of organic mass in compost and shown in Fig. 3. In the initial stage, the degradation of organic matter in Run A increased slowly and only 7.93% of initial organic matter was reduced till day 10. During composting, transformations of substrates involved various biochemical reactions. The low activity in Run A was corresponding to a decrease in the pH values measured in this pile, compared to the reactors prepared with other amendments. This low pH level of in the initial stage is likely to be an important factor inhibiting the composting process. In the Run B and Run C, the degradation was undertaking a rapid increase after the lag of 1 day, but the increasing patterns were significantly different ($p < 0.05$). The degradation percentages in Runs B and C were equivalent to 48.35% and 55.97% at day 10, respectively. The amendment of CA showed better degrading performance than that in the control. It has been also observed that the degradation rate of organic matter under appropriate pH control, such as liming and adding sodium acetate, was faster than that in the experiment without any adjustment [30,34]. Compared with the amendment of CA only, the degradation of food waste mixture was further increased with an addition of both CA and UA, which caused a higher metabolic activity in the treatment.

in Run B and Run C. This trend was also similar to that observed in other composting processes [26]. It is apparent that the compost of Run B and Run C was stabilized after 23 days of composting. The temperature profile of Run A did not evolve strictly around the constant temperature. Instead, the downward trend for Run A was also observed after 32 days of composting and the temperature of Run A could be close to the ambient environment after 39 days of composting (data not shown).

The temperature changes could reflect the microbial activity and the evolution of the composting process. Aeration plays an important role in the maintenance of high temperature during composting. Previous studies suggested that CA would be a suitable bulking agent for composting process [27]. Thus the enhanced porosity by CA amendments allows plenty of air to be trapped and utilized for metabolic heat generation by aerobic organisms, leading to a higher temperature. Furthermore, the enzyme-catalyzed hydrolysis of UA often accompanied with the generation of easily assimilable sources of nitrogen and energy, which can facilitate the microbial growth [28]. The higher temperature observed in UA-amended series during the initial stage might be due to the enhanced intensity of aerobic microbial action.

As depicted in Fig. 2b, the changes in pH during composting process were not uniform for different reactors. The initial pH of Run A, Run B and Run C were 5.79, 6.02 and 6.07, respectively. Unlike many other solid wastes, the raw household waste such as food waste was often characterized by a low pH [13]. The initial pH level
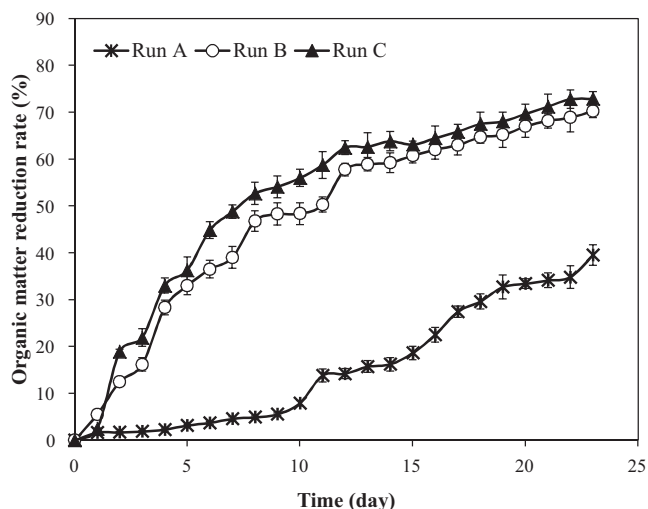
Fig. 3. Organic matter reduction in the composting process.

The intensity of degradation in Run A was enhanced during the late stage. After 23 days of composting, 39.51% of the total organic matter weight in Run A was lost. As for the Run B and Run C, the significant change in degradation of organic matter occurred during the first 12 days, while a slower rate of organic matter losses was observed compared in the successive 11 days. The degradation process almost stopped when readily biotransformed material was fully consumed. At the end of the composting, 70.24% of original organic substrate was degraded in Run B at day 23, while the corresponding values for the Run C was 72.87%.

Mineralization and humification during composting are the main processes causing the transformation of organic waste [1]. The organic waste can be converted into stabilized product with humus-like property, along with the emission of some other metabolic products like inorganic elements, volatile organic compounds and biomass [35]. Processes with the composting of some organic wastes showed the limited total weight losses, which were often due to the presence of resistant organic substrates such as cellulose, hemicellulose and lignin in substrate [9]. However, the mixture in present study showed a high degradation rate. Food waste is generally characterized by abundant assailable organic matter, resulting in more intensive process of mineralization by microorganisms. It has been reported the low microbial activity in low pH range was probably related to a lag phase of composting [30]. Fang and Wong [33] reported that the amendment of coal fly ash might had the adverse effect on the decomposition activity in sludge compost. Compared with the pH level in their study, a much lower pH level was observed in present experiment. Thus the addition of CA could neutralize the acidity and facilitate the degradation of organic compost. This also indicates the influence of CA is highly correlated with the characteristic of composting substrate. When amended with both CA and UA, degradation intensity and temperature would further increase especially in the early stage. The presence of UA might supply a suitable amount of nutrient. The metabolic activity could be improved, resulting more transformation from substrate into end products. But the results also showed that such influence became less significant during the final phase.

3.3. Variations of O_2 uptake during composting

The O_2 uptake rate underwent considerable change during the composting process (Fig. 4a). In Run A, the O_2 uptake rate was below 2.43 mg/(g-dry solid h) before day 15, which was significantly lower ($p < 0.05$) than O_2 uptake rate observed in Run B or
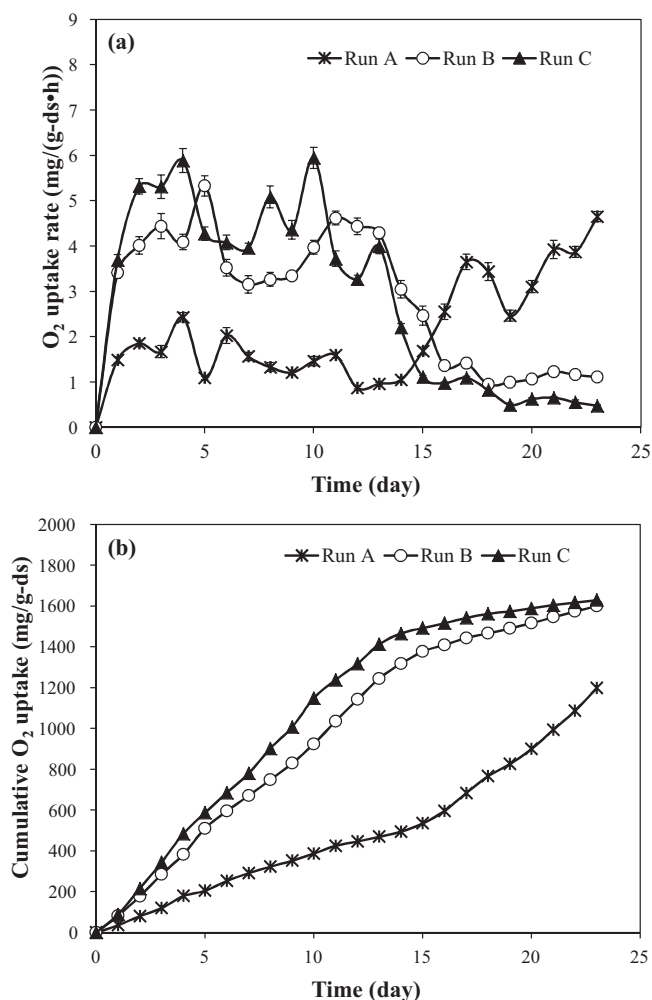

Fig. 4. Variations of O_2 uptake rate (a) and cumulative amount of O_2 (b) during composting.

Run C. The O_2 uptake rate of Run C fluctuated between 3.27 and 5.95 mg/(g-ds h) from day 1 to day 13. The O_2 uptake rate in Run C was significantly higher ($p < 0.05$) than that in Run B in the first 10 days. Run B reached its maximum O_2 uptake rate of 5.33 mg/(g-ds h) at day 5. The aerobic consumption rate can be selected as a suitable indicator to assess composting performance and end-product stability [9]. Aeration is important for the success of any composting procedure, particularly for the in-vessel composting system. In our previous study, different aeration rates have been compared, based on the composting efficiency, end-product quality, air pollution and energy consuming [36]. An aeration rate of 0.1 vvm was recommended as a suitable rate for food waste composting in this system. The microorganisms could degrade the organic matter in food waste to CO_2 and NH_3 with the consumption of O_2. The low O_2 uptake amount in the unamended series was mainly correlated with the limited degradation of food waste. When the CA was added, more intense degradation might need more O_2 for biochemical reaction within the pile. Also, the presence of CA could improve the porosity of the food waste compost, resulting that more O_2 would be retained and utilized during composting. As for the series with CA and UA, besides the degradation of food waste, the transformation and utilization of UA could also contribute to the consumption of oxygen [37].

The plots of the cumulative O_2 versus time showed an increase of O_2 during the composting process (Fig. 4b). As the degradation of compost increased, O_2 uptake was more rapid. Cumulative

amounts of O_2 uptake in Run A were 386.91 mg/g-ds after 10 days, 924.69 mg/g-ds in Run B and 1149.52 mg/g-ds in Run C. The cumulative amount of O_2 uptake in Run A was significantly less ($p < 0.05$) than that of Run B or Run C within these 23 days. The cumulative O_2 uptake amounts at day 12 were equivalent to 71.35% and 80.82% of total O_2 uptake amounts after the experimental time of 23 days in Run B and Run C, respectively. It indicated the O_2 consumption mainly occurred during the first half of the process for these two series. During the late phase of composting, the reaction was less intensive and O_2 uptake increased less significantly. The higher O_2 uptake amount was observed in the presence of CA and UA than with CA only, which was due to the stronger demand for O_2 by microorganisms. After 23 days of composting, the increase of O_2 uptake amount ceased for Run B and Run C. The transformation of most biodegradable compounds had already taken place and thus no more significant O_2 demands were shown due to the reduced substrate and biological activity in these piles. As compared with Fig. 2, the O_2 uptake evolution patterns in the compost reactor could also coincide with the changes in the temperature. These patterns were in accordance with those observed during the other aerobic composting processes [34].

3.4. Evolution of microbial population

The decomposition of food waste is carried out by various groups of microbial populations, which can utilize various complex organic materials in substrates. The microorganisms in the compost would develop according to the temperature of the mass. The succession of microorganism communities might also have a potential influence on the biodegradation capabilities and oxygen consumption requirements of the composting process [38]. Fig. 5a depicts the changes in thermophilic microorganism population of all treatments. At the beginning of composting, the population of thermophilic microorganisms in Run A was 3.63 $\log_{10}$ CFU/g. Run B and Run C with CA amendment had a slightly lower number of thermophilic microorganisms than that of Run A. This might be due to the adverse influence of salinity and alkalinity natures of CA [39]. The initial thermophilic microorganism quantities did not differ significantly between Runs B and Run C. As the process proceeds, the microorganisms within the compost seemed to tolerate and adapt to the environment quickly. All observed thermophilic microorganisms increased, but with different patterns in these reactors.

At day 6, the population of thermophilic microorganisms in Run A, Run B and Run C was 5.71, 7.24 and 8.90 $\log_{10}$ CFU/g, respectively. The population of thermophilic microorganisms with CA amendment outnumbered that without CA amendment during the initial stage. This is in contrast to Fang et al. [40], who found thermophilic microorganism population could be significantly inhibited in the sewage sludge compost with coal fly ash amendment. Such difference could be mainly ascribed to the differences of waste properties. The low pH level in composting of food waste might lead to the limited proliferation of microorganisms. The addition of CA could neutralize the acidic environment, which would be favorable for the microbial activities. Correspondingly, the higher temperature and faster degradation could be achieved in CA-amended series during this stage (Figs. 2 and 3). In addition, a higher population of thermophilic microorganisms in Run C was noticed at day 6 and day 12. It suggested that the coexistence of CA and UA might further facilitate the enhancement of microbial population. Microbial numbers can significantly increase when a nitrogen source is used to initiate composting [41]. Moreover, the rapid increase of thermophilic microorganism population is often accompanied with the high level of urease, which could facilitate the transformation of UA as well as other nitrogen components [42,43]. That also might lead to the more intense
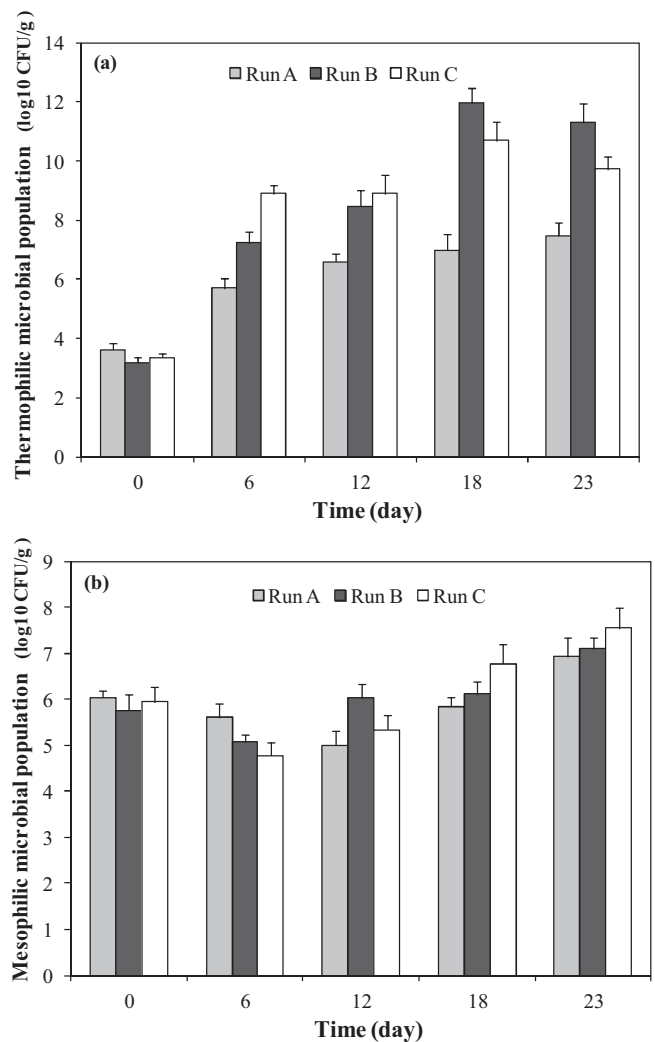

Fig. 5. Evolution of thermophilic (a) and mesophilic microbial population during composting.

composting process with the addition of both CA and UA in this stage.

In spite of the decreased temperature, the thermophilic microbial population still increased at day 18, representing an extension of the active phase. After that, there was still an increase about the population of thermophilic microorganisms in Run A, while the population of thermophilic microorganisms in Run B and Run C began to decrease. At day 23, the population of thermophilic microorganisms in Run B and Run C was 11.30 and 9.72 $\log_{10}$ CFU/g, respectively. The lower amount of microorganisms was observed in series with both CA and UA. It indicated the additional amendment of UA showed the inhibitory effect on the population of thermophilic bacteria at the final stage of composting. This might be related to the higher level of pH and ammonia emission, which were potentially detrimental to the microorganisms.

As for the mesophilic microorganism during the composting process, the results showed that mesophilic microorganisms were present throughout the composting period. The initial populations of mesophilic microorganism in Run B and Run C were 5.76 and 5.95 $\log_{10}$ CFU/g, respectively (Fig. 5b). The amendment of CA still showed a little adverse effect on the microorganisms. Then the composting mixture of Run B and Run C showed a decrease of mesophilic microorganism when entering thermophilic phase. This was similar to the results of some previous studies [26]. The addition of lime has been reported to pose adverse effect on
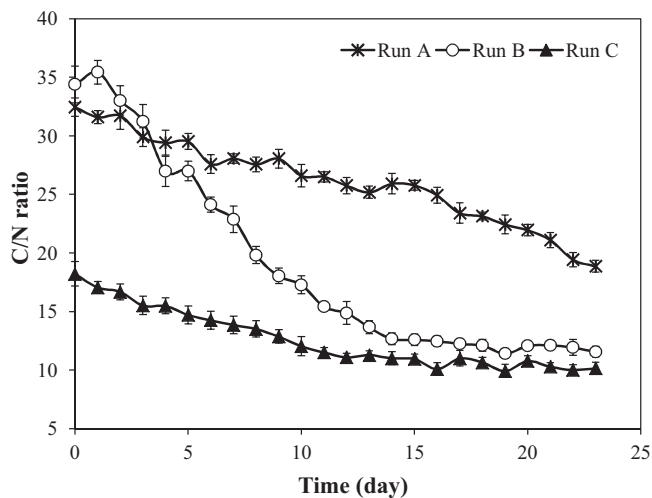
Fig. 6. Changes of C/N ratio in compost.

the mesophilic microorganism population development [43]. In present study, however, the mesophilic microorganism showed better development in CA-amended series than that in CA-free series after day 6. Since the thermophilic phase was corresponding with significant mass degradation and high oxygen consumption (Figs. 3 and 4), thermophilic bacteria might play a more important role in decomposition of food waste than mesophilic bacteria. Mesophilic bacteria often showed limited degrading activity for organic matter during this stage [44]. At day 12, the populations of mesophilic microorganism in Run B and Run C were to 6.02 and 5.34 $\log_{10}$ CFU/g. Less mesophilic microorganisms were observed in Run A, which also reflects the lower microbial activity of the mixture at that time. When temperature declined later, mesophilic microorganism population increased again. And then there was no further decline during the following stage.

3.5. Changes of C/N ratio

The variations of C/N ratios obtained in these experiments are presented in Fig. 6. The initial C/N ratios in the substrates of Run A, Run B and Run C are 32.46, 34.39 and 18.22, respectively. The C/N ratio in the range 25–35 has been reported to be adequate for composting, because the microorganisms require 30 parts of C per unit of N during metabolism [9]. In present study, the slightly higher C/N ratio in Run B may be attributed to the amendment of CA in which unburned carbon often exists [45]. But the nitrogen content in added UA could lead to the relatively lower initial C/N ratio in Run C. This scenario could reflect the reality that food waste in composting mixture coexists with other manure wastes, which are often characterized by the low C/N ratio [1]. The C/N ratio of all treatments generally decreased over time, except there was a slight increase in Run B at early stage. A major portion of the carbon is used by the microorganisms as the energy source and released as carbon dioxide, whereas the nitrogen is partially used for synthesis of proteins. Thus more significant loss of carbon could occur in compost, leading to the decrease of C/N ratio.

The C/N variation of different reactors showed different trends. Although Run A and Run B had a close C/N ratio initially, there was a more significant decrease of C/N ratio in Run B subsequently. At day 4, the C/N ratios for Run A and Run B were 29.42 and 26.98, respectively. Then C/N ratio of Run B remained significantly lower ($p < 0.05$) than that of Run A during all the following process. The slower descending trend of C/N ratio in Run A might be due to the lower degradation rate of food waste during composting. The good quality compost is often characterized by a C/N ratio lower than 20

[1,32]. By day 23, the C/N ratios of Run A and Run B had decreased to 18.87 and 11.56, respectively. Additionally, a decreasing trend of C/N ratio was also observed in Run C. But there was obvious fluctuation of C/N ratio during the later stage. Similar variation of C/N has been also observed in previous study about manure composting [46]. In the coexistence of CA and UA, the compost showed a high pH level within the last period. The intermittent increases in C/N ratio suggested that N was possibly lost through ammonia volatilization. The nitrogen immobilization by nitrogen-fixing bacteria during the mesophilic period of composting might also contribute to this effect [31].

4. Conclusion

The influence of CA and UA amendment on the in-vessel composting of composite food waste was investigate in this study. The results showed that the amendment of CA and UA could cause a more significant increase in temperature, particularly in the first half of the process. The alkaline components in CA could buffer the acidity of the composting mixture, while a slightly higher pH level was shown in the series with both CA and UA. When amended with CA and UA, degradation intensity would further increase especially in the early stage. The higher O_2 uptake amount was observed in the presence of CA and UA than with CA only, which was due to the stronger demand for O_2 by microorganisms. Both thermophilic and mesophilic microorganisms were present throughout the composting period. But different trend was observed in the series with both CA and UA. In the presence of CA and UA, the C/N ratio of food waste was undertaking a similar decreasing trend, while the C/N level was lower than that of UA-free series. The results imply that the coexistence of manure and some particular industrial waste might pose both positive and potentially negative effect on food waste composting. Appropriate strategies should be applied to adjust the composting process under such complex environment. Further study is needed to investigate the influences of other components in manure and industrial waste composting as well as the dynamic correlation of various process indictors to get better quality product.

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