Research Article

Effect of C/N on Water State during Composting of Kitchen Waste and Vegetable Waste Mixture

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The objective of this study was to evaluate the effects of the C/N ratio on the water state changes during the composting of kitchen waste (KW) and vegetable waste (VW) mixtures. The C/N ratios in KW and VW were 50.70 and 27.07, respectively, and the VW was added to the KW to amend the C/N ratio. Five composting treatments were used, R1 with 0% KW, R2 with 25% KW, R3 with 50% KW, R4 with 75% KW, and R5 with 100% KW, and the initial C/N ratios increased in the order R1 < R2 < R3 < R4 < R5. As the composting process progressed, the capillary water (CW) and multi-molecular-layer water (MMLW) were changed into entrapped water (EW), and a high C/N ratio could delay the changes in the water state. The percentage of EW and CW significantly positively correlated with the C/N ratio during the composting of KW. The composting process performed better in treatments R2 and R3 than in the other treatments, and it was found that treatments R2 and R3 each had a lag phase of around 4 d until the water states started to change.

1. Introduction

Composting has been used to dispose of kitchen waste (KW), which is the residue from meals and is a typical type of organic waste [1]. The moisture content (MC) is a key parameter in composting because water is the medium in which the nutrients required for microbial activity are dissolved and transported [2], and the MC can affect the air-filled porosity and thermal conductivity of the waste material [3]. A low MC is unfavorable for microbial growth in composting, and a high MC can suppress the mass transfer of air. The MC generally decreases as the composting process progresses [4]. Therefore, a balanced MC should be maintained to achieve the most mature composting possible.

The composting of KW system is a typical mixed organic matter system, and the water is present as two fractions: free water and bound water [5]. Free water can be divided into entrapped water (EW) and capillary water (CW), and bound water consists of multi-molecular-layer water (MMLW) and monolayer water. Monolayer water is closely integrated with the nonaqueous components and cannot be removed by heating at ambient pressures [6], and the percentage of monolayer water stays around 0.5% [7]. Therefore, the EW, CW, and MMLW are the focus of the MC balance during the composting of KW.

It has been shown in many studies that the chemical composition of food and sludge affects the water states within them [8–10]. The main chemical components in KW are crude fat, crude protein, and carbohydrates [11]. Crude fat and carbohydrates lack nitrogen, but the nitrogen content of crude protein is about 16% [12]. The carbon contents of the components decrease in the order crude fat > carbohydrates > crude protein [13]. It can be seen, therefore, that the C/N ratio is different in each component, and this has led to the C/N ratio being used to describe the characteristics of the chemical components in composting systems [14]. In our previous studies [15, 16], we found that the C/N ratio decreases as the percentage of EW increases and the percentage of CW decreases, because a large amount of biodegradable organic matter is degraded and the nitrogen that is present becomes concentrated. This indicates that the water states should be affected by the C/N ratio during the composting of KW.

The nitrogen content of KW from Chinese canteens has been found to be 1.05–1.26%, and the carbon content has

TABLE 1: The material composition and C/N ratio for the five composting treatments.

Treatments	R1	R2	R3	R4	R5
Air-dried KW (%)	0	25	50	75	100
Air-dried VW (%)	100	75	50	25	0
C/N	27.07	31.00	38.32	42.71	50.70

been found to be 52.15–54.78%, giving high C/N ratios of 41.26–52.03 [12]. A material with a lower C/N ratio should be mixed with the KW to decrease the initial C/N ratio. Vegetable waste (VW), which is generated during food pretreatment processes, has a lower C/N (17.4–21.7) than KW [11, 17], and VW is also a typical organic waste that is effectively biodegraded, so VW was used to amend the KW C/N ratio in the study presented here.

In the study presented here, waste material with five different KW-to-VW ratios was prepared to achieve five different C/N ratio gradients during the composting of KW. Variations in the C/N ratio and the changes of water states (EW, CW, and MMLW) were monitored as the composting process progressed.

## 2. Materials and Methods

2.1. Materials

2.1.1. KW and VW. Fresh KW and VW were collected from Zhejiang Gongshang University's canteen. The fresh KW was drained of excess fat and water by placing a 5 cm thick layer of the fresh KW on a 3 mm plastic mesh screen and leaving it for about 10 min. This pretreatment caused the wet weight of the fresh KW to decrease by 32.8% because of the loss of fat and water. The components in the drained KW were determined, and the protein-rich material (meat and bean products), vegetable material, and starch-rich material (rice and noodles) contents were found to be 11.10%, 16.12%, and 72.78% of the dry weight, respectively. The C/N ratios of the protein-rich material, vegetable material, and starch-rich material in the drained KW were 11.72, 22.50, and 54.36, respectively.

The drained KW and fresh VW were cut into pieces with diameters of 5.0 ± 0.5 cm and allowed to dry naturally. The air-dried KW and VW were kept at 60% MC and were stored at −20°C until they were used. Detailed information about the air-dried KW and air-dried VW is shown in Table 1.

2.1.2. Inoculums for Composting. High-performance mixed flora, containing microorganisms that could decompose starch, glucose, and protein, was isolated in a previous study [18] and stored at −80°C in glycerol.

Before inoculating the waste material, the high-performance mixed flora was activated in a Luria–Bertani culture medium [19]. The concentration of the high-performance mixed flora that was used was higher than 1×10^{15} CFU mL^{-1}.

2.2. Experimental Setup and Operation. Each composting experiment was performed in a 16 L (effective volume) plastic
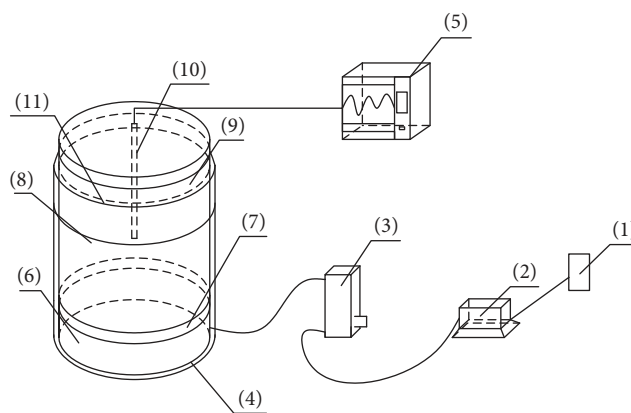
(1) Electronic relay
(2) Air pump
(3) Gas rotameter
(4) Reactor
(5) Temperature recorder
(6) Aeration chamber
(7) Rubble layer
(8) Reactor chamber
(9) Overlay
(10) Temperature probe
(11) Insulating layer

FIGURE 1: Experimental setup.

vessel (Figure 1), five composting treatments were performed, and each group of treatments had three replications at the same time. The five composting treatments were called R1, R2, R3, R4, and R5, and each contained a mixture of air-dried KW and air-dried VW at a different ratio. Detailed information on the compositions of the waste mixtures used in the five composting reactors and the C/N ratios in them is shown in Table 1. All five treatments were performed in a greenhouse (at 29 ± 1°C) and each had a 0.05 L min^{-1} L^{-1} aeration rate.

Each reactor contained 6 kg of a waste mixture with an initial MC of 60%, and the high-performance mixed flora concentrate was added to each reactor at a rate of 1 mL kg^{-1} of material.

The treatments were performed for 16 d. The temperature of each reactor was recorded by the temperature recorder (Figure 1) every 20 s, and samples were collected for analysis from each reactor on days 0, 2, 4, 6, 8, 10, 12, 14, and 16. Each sample was a composite of four samples taken through the whole depth of the waste material, with a total weight of about 80 g. To take a sample, the cross section of the vessel was marked into quarters, and a sample of about 20 g was taken from the center of each quarter, through the full depth of the waste material. Each sample was immediately cut into pieces (<5 mm diameter) using a multifunctional food mixer (Midea MJ-25BM05C, Foshan, China). The prepared samples

were either immediately analyzed or temporarily stored at 4°C.

2.3. Analytical Methods. The water states, MC, pH value, and electrical conductivity (EC) of the samples were analyzed on the day the samples were collected [20]. After the water states and MC in a sample had been determined, the dry sample was milled and stored at room temperature for the subsequent determination of the total carbon (TC) [21, 22], total nitrogen (TN) [23], alkali-extractable organic-C (C_{EX}), humic acid-like organic-C (C_{HA}) [24], neutral detergent solute (NDS), hemicellulose, cellulose, and lignin contents [25]. Samples collected on day 16 were analyzed for C_{EX} and C_{HA} and samples collected on days 0, 2, 6, and 16 were analyzed for NDS, hemicellulose, cellulose, and lignin. The percentage of humic acids (PHA) was used to evaluate the humification level of the material that had occurred during composting using [24]

$$PHA = 100 \times \frac{C_{HA}}{C_{EX}}. \tag{1}$$

The water states were measured by gradient evaporation described in detail in the Supplementary Material (available online at https://doi.org/10.1155/2017/9409145) (Table S1 and Fig. S1). 30, 40, 50, 60, 70, 80, 90, 100, and 105°C were set with the water state analysis; the residence time of each temperature except for 105°C was 1 h; the residence time of 105°C was 2 h. The water removed at 30, 40, and 50°C was EW, the water removed at 60 and 70°C was CW, and the water removed at 80, 90, 100, and 105°C was MMLW. And the total amount of water removed during the gradient evaporation process was assumed to be the MC.

2.4. Statistical Analysis. Analytical data were assessed using SPSS 17.0. One-way ANOVA was used to test the statistically significant differences among the treatments and each period.

3. Results and Discussion

3.1. Effect of the C/N Ratio on Changes in the Water States. As is shown in Figure 2, using a higher proportion of KW in the waste mixture gave it a higher initial C/N ratio because the KW contained 72.78% starch-rich material by dry weight and the starch-rich material had a high C/N ratio of 54.36. As the composting process progressed, the C/N ratios in the R1, R2, R3, R4, and R5 treatments decreased by 8.70, 15.74, 23.75, 24.06, and 27.88, respectively, suggesting that a higher proportion of KW in the waste mixture led to more effective decomposition of carbonaceous organic material.

The C/N ratio is one of the parameters that can be used to evaluate the maturity of compost, and it has been suggested that a C/N ratio below 15 indicates that the maturity of composting product is acceptable [26]. As can be seen in Figure 2, the final C/N ratios in the R1, R2, R3, R4, and R5 treatments were 18.37, 15.26, 14.57, 18.65, and 22.81, respectively, suggesting that the R2 and R3 treatment products were more mature than the products of the other treatments. The optimal initial C/N ratio in KW for composting was therefore determined to be 31.00–38.32.
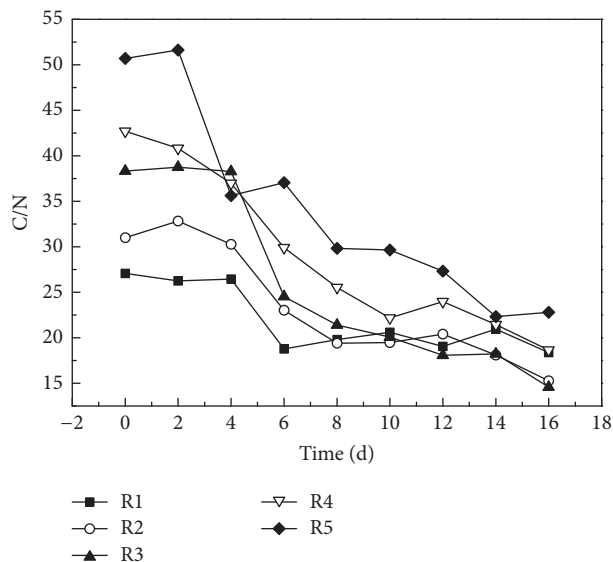

Figure 2: C/N for the composting of KW.

The water state distributions and water state changes that were found throughout the experiment are presented in Figure 3. The water state clearly changed between 0 d and 2 d in all of the composting treatments, and this may have been caused by the effects of thawing the original waste materials, which had been stored at −20°C, leading to some of the frozen water in the stored material becoming liquid water in the waste mixture used in the composting treatments [27]. This liquid water would have been classed as EW during the water state testing procedure, so the waste mixtures would have had high EW contributions to the MC on day 0. Some of the liquid water was redistributed into the CW and MMLW in all five composting treatments as the composting process progressed. Therefore, we took the water state on day 2 to be the primary initial water state in each composting system.

The lowest EW contributions to the MC in the R1, R2, R3, R4, and R5 treatments were 63.48 ± 0.18%, 56.93 ± 1.72%, 57.53 ± 4.65%, 39.73 ± 2.59%, and 36.53 ± 0.89%, respectively. The CW contributed more than 25% of the MC for periods of 4, 4, 4, 14, and 4 d in the R1, R2, R3, R4, and R5 treatments, respectively, and the CW contributed more than 20% of the MC in the R5 treatment for the whole composting process. The MMLW contributed more than 10% of the MC for periods of 0, 4, 12, and 14 d in the R1, R3, R4, and R5 treatments, respectively, and the MMLW contributed more than 10% of the MC in the R2 treatment on day 6 only. The changes in the water states (EW, CW, and MMLW) described above showed that the initial C/N ratio in the waste mixture in the composting system affected the changes that occurred in the water states and that a high initial C/N ratio usually indicated that more water would be present as CW or MMLW. The differences in the changes in the water states between the different treatments may have been caused by the notion that there were more readily biodegradable organic carbon and starch-rich materials in the composting
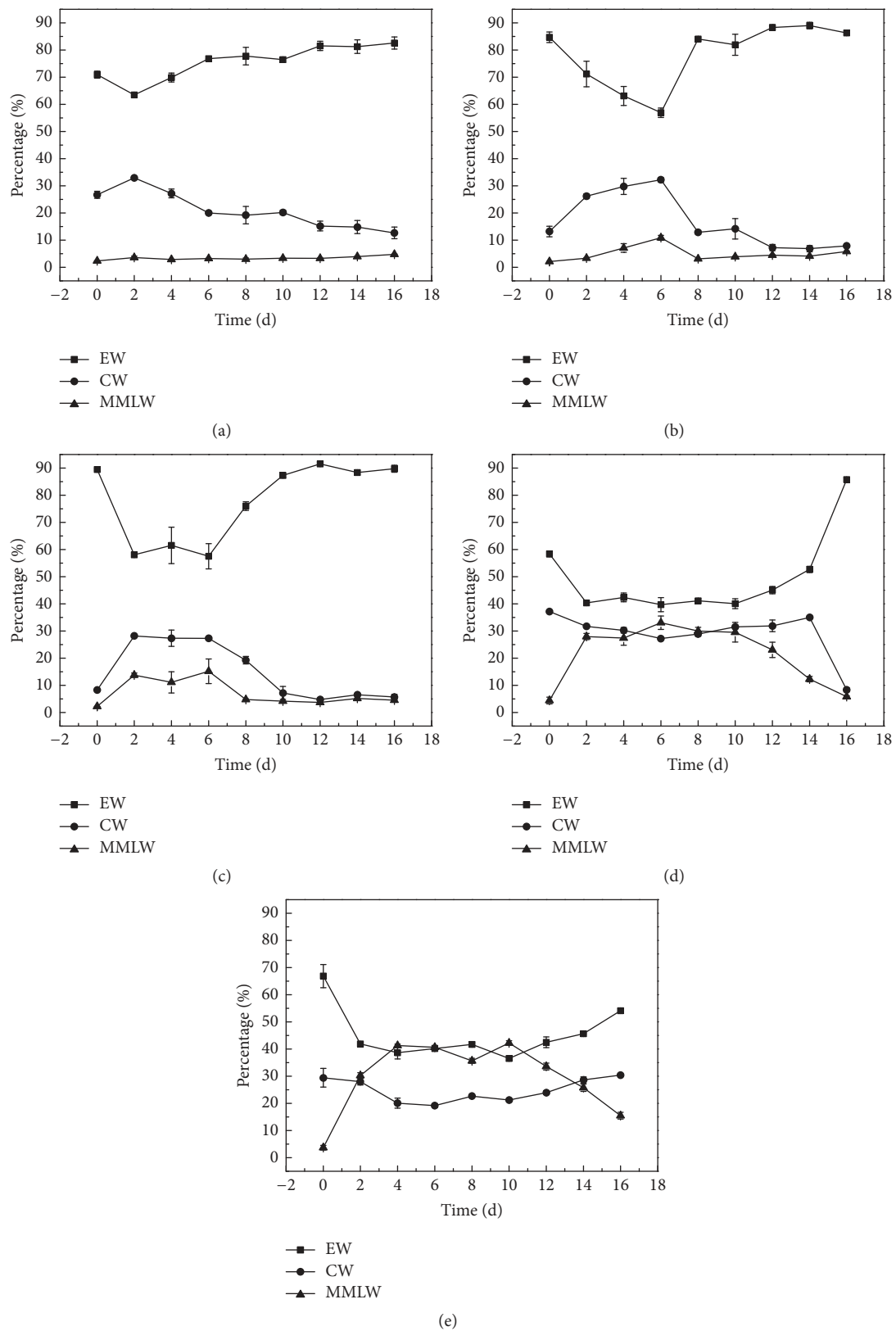
(a)

(b)

(c)

(d)

(e)

Figure 3: Variation of water states (EW, CW, and MMLW) during the composting process. (a), (b), (c), (d), and (e) represent R1, R2, R3, R4, and R5, respectively.

systems with higher C/N ratios than in the systems with lower C/N ratios, because most readily biodegradable organic carbon is strongly hydrophilic [28]. This suggests that large amounts of water would be drawn to the material that is mainly composed of readily biodegradable organic carbon. Such water would not be able to move freely. At the same time, starch-rich substances, such as rice, had smaller particle sizes than the protein-rich substances and the vegetables in the KW used in the experiments. The air-filled porosity of waste material is affected by the particle sizes present [29], so both air movement and changes in the water states may have been lower in the composting systems with higher C/N ratios than in the systems with lower C/N ratios.

Changes in the water states in the R1 treatment mainly occurred in the EW and CW as the composting process progressed, but, concurrently, changes in the EW, CW, and MMLW water states all occurred in the R2, R3, R4, and R5 treatments. Changes in the water states followed a continual trend between days 2 and 16 in the R1 treatment, and changes in the water states occurred after days 6, 6, 10, and 10 in the R2, R3, R4, and R5 treatments, respectively. This suggests that a higher C/N ratio could inhibit changes in the water states during the composting of KW, although differences in the changes in the water states between treatments were affected not only by the C/N ratio but also by the degradation of organic matter, the temperature, and the degree of aeration. The degradation of organic matter could destroy the capillary structure and release the CW and MMLW, transferring MMLW and CW into EW. A high temperature could also promote changes in the water states, and treatments R4 and R5 both had a short thermophilic phase (Figure 5(a)), which may be one of the reasons why the water state remained in a dynamic equilibrium in the R4 and R5 treatments for most of the experimental period. A high degree of aeration could remove water and promote the release of MMLW or CW to form EW.

As can be seen from Figure 4, there was a significant correlation between the EW contributions to the MC and the C/N ratio during the composting of KW ($R^2 = 0.55$, $p = 2.53 \times 10^{-8}$). A significant correlation between the CW contribution to the MC and the C/N ratio was also found ($R^2 = 0.83$, $p = 3.33 \times 10^{-16}$), but no significant correlation was found between the MMLW contribution to the MC and the C/N ratio ($R^2 = 0.07$, $p = 5.48 \times 10^{-2}$). This suggests that controlling the C/N ratio could be used to regulate the water states during the composting of KW.

3.2. Evolution of the Temperature and the MC. As is shown in Figure 5(a), the temperature in each of the treatment systems varied in similar ways during the experiment, and each had three degradation phases: a mesophilic phase, a thermophilic phase, and a curing phase [30]. However, the temperature attained during the thermophilic phase was not the same in all of the treatments; the temperature in the R1 treatment remained at around 50°C but the temperatures in the R2, R3, R4, and R5 treatments remained at around 55°C. This suggests that heat was retained by the composting system more effectively when the EW contribution to the MC was lower than when it was higher. The temperature remained at around 55°C for about 6 d in the R2 and R3 treatments but for about 3 d in the R4 and R5 treatments. This suggests that if the MMLW contribution to the MC remained high (MMLW > 10% of MC) for a long time (Figures 3(d) and 3(e)), the microbial activity will be inhibited and, therefore, the production of heat will be inhibited. This might have been because MMLW could not be exploited by the microorganisms; moreover, a high MMLW contribution to the MC might make the waste material agglomerate, inhibiting the mass transfer of air.

The MC generally decreased throughout each of the treatments (Figure 5(b)). Between days 10 and 16, the MC was significantly higher in the R5 treatment than in the R1, R2, and R3 treatments ($p < 0.05$), and between days 12 and 14 the MC was significantly higher in the R4 treatment than in the R1, R2, and R3 treatments ($p < 0.05$), although the MC in the R4 treatment was similar to the MC in the R3 treatment on day 16. These changes in the MC in the R4 and R5 treatments were consistent with the changes that were found in the EW content (Figures 3(d) and 3(e)). This suggests that keeping the EW contribution to the MC at a low level (<55%) could inhibit the removal of water from the composting system.

3.3. pH and EC. The changes found in the pH of the waste material during each of the treatments are shown in Figure 6(a). The pH of treatment R1 reached 7.0 on day 6, but the pH values in the other treatments remained below 6.0 at that time. The EW contribution to the MC was also higher in the R1 treatment than in the other treatments on day 6 (Figure 3). The pH values between days 8 and 16 were significantly lower in the R4 and R5 treatments than in the R1, R2, and R3 treatments and lower than what was found in most other composting systems that have been studied [1, 31]. The EW contributions to the MCs were also lower in the R4 and R5 treatments than in the other treatments during that period (Figure 3). The behavior of the pH during the experiment suggests that high CW and MMLW contents inhibited the mass transfer of air through the waste, and the poor oxygen supply caused the aerobic biodegradation rate to be low and hydrolytic acidification to occur. In addition, the different initial pH values and C/N ratios in the different treatments may have affected the pH changes that occurred during the composting process because a low initial pH would have inhibited microbial activity [32] and a high C/N ratio would indicate that less nitrogen would be available for creating the ammonia that would contribute to increasing the pH during the composting process [33].

Similar upward trends in the changes in the EC values were found for all of the treatments (Figure 6(b)). The EC reflects the degree of salinity in the composting product [34], so the EC in a composting system could be affected by the release of mineral salts and the concentrating effect caused by a decrease in the MC (Figure 5(b)). The different EC values that were found in the different treatments during the composting process in our study were caused by the initial EC values and the removal of water from the composting systems.
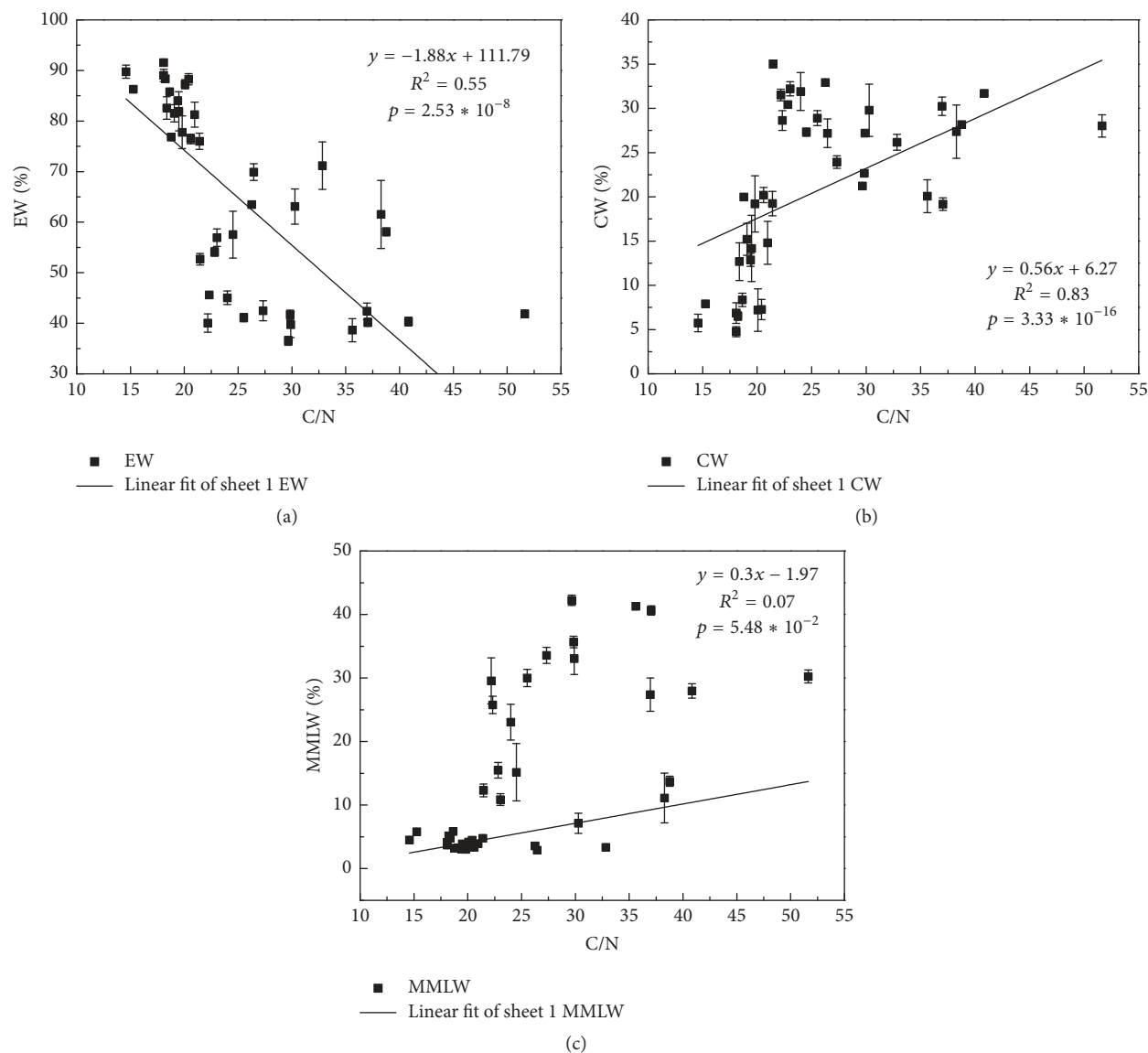
(a)

(b)

(c)

FIGURE 4: (a) Correlation between the percentage of EW and C/N during the composting process in all five composting treatments, (b) correlation between the percentage of CW and C/N during the composting process in all five composting treatments, and (c) correlation between the percentage of MMLW and C/N during the composting process in all five composting treatments.

TABLE 2: The final PHA for the five composting treatments.

Treatments	R1	R2	R3	R4	R5
Final PHA (%)	7.11 ± 2.44	10.60 ± 0.29	12.24 ± 1.34	8.64 ± 0.30	8.35 ± 0.18

3.4. PHA. The PHA has been defined as the percentage of C_{HA} in C_{EX}, and it has been used as an index of the maturity of the composting product [35]. C_{EX} is produced and C_{HA} increases during the composting process, and the fulvic-acid-like organic carbon content will gradually decrease as it is transformed into C_{HA}, so a higher PHA indicates a more mature product [36]. As can be seen from Table 2, the humification levels were significantly higher in the R2 and R3 treatments than in the other treatments ($p < 0.05$), and, as shown in Figures 3 and 5(a), the behavior of the temperature

and changes in the water states at the same time were also more beneficial to composting in treatments R2 and R3 than in the other treatments. This suggests that a high temperature and a reasonable water state distribution could promote the maturation of the composting product.

3.5. Biochemical Fractions. As is shown in Figure 7, the initial NDS content in each treatment suggested that the NDS content was significantly lower in the KW than in the VW. The NDS content followed a similar decreasing trend
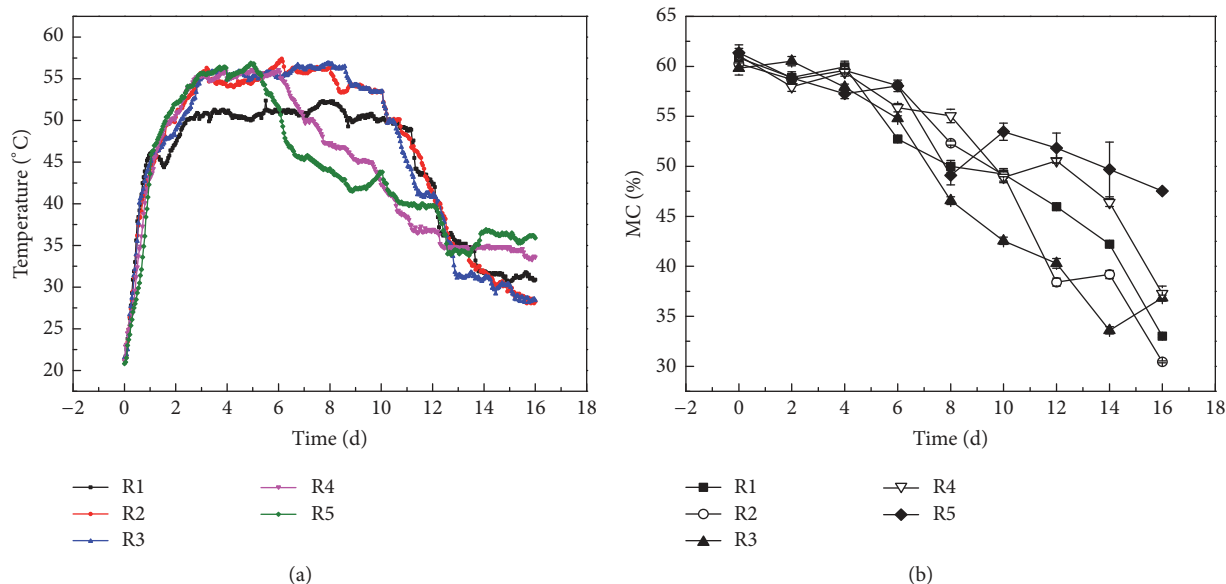
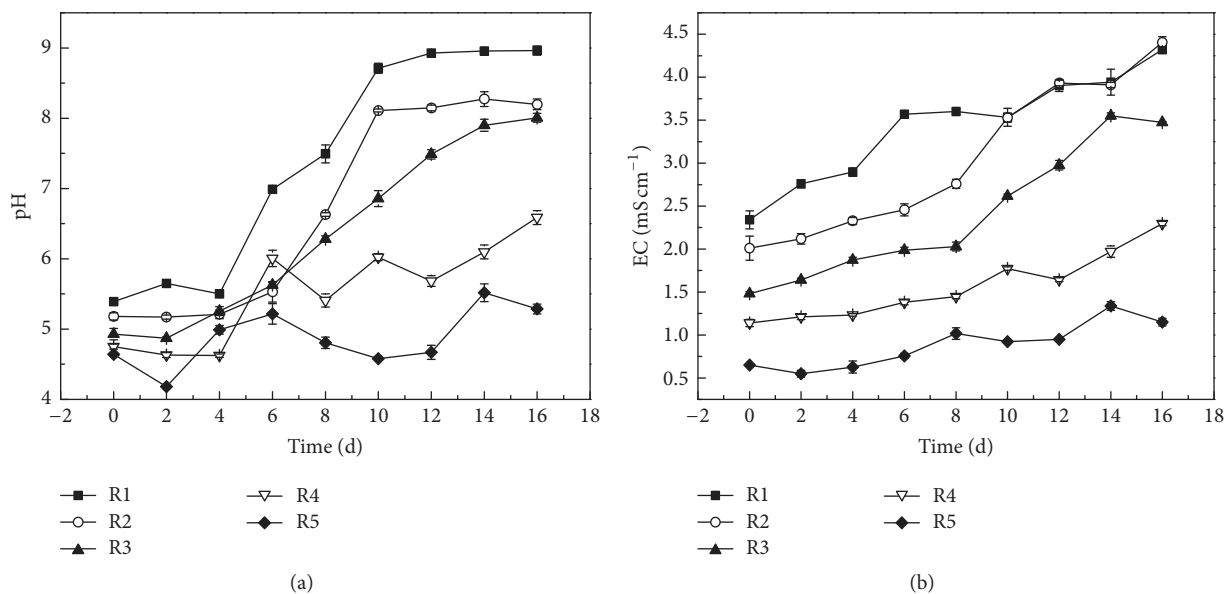FIGURE 5: (a) Temperature for the composting of KW and (b) MC for the composting of KW.

FIGURE 6: (a) pH for the composting of KW and (b) EC for the composting of KW.

in each of the treatments, whereas the neutral detergent fiber (NDF), hemicellulose, cellulose, and lignin contents followed increasing trends. This suggests that NDS was more easily biodegraded than were the total NDF and the three individual NDF fractions, and this phenomenon may have been caused by the NDS mainly being contained in the starch, protein, and fat components, which were easily used by the microorganisms.

As the changes in each biochemical fraction in each treatment show (Figure 7), the NDS and NDF changed most dramatically in the R1 treatment, and that R1 treatment had no lag phase in the changes in the water states, unlike the other treatments (Figure 3). This suggests that using

only VW in a composting system was not conducive to the decomposition of the NDF and that an appropriate lag phase in changes in the water states during the composting of KW was conducive to the decomposition of the NDF.

4. Conclusions

Introducing VW into KW can allow the C/N ratio to be adjusted to a specified value for composting. The transfer of CW and MMLW to EW clearly occurred as the composting process progressed. Significant positive correlations were found between the EW contribution to the MC and the C/N ratio ($R^2 = 0.55, p = 2.53 \times 10^{-8}$) and between
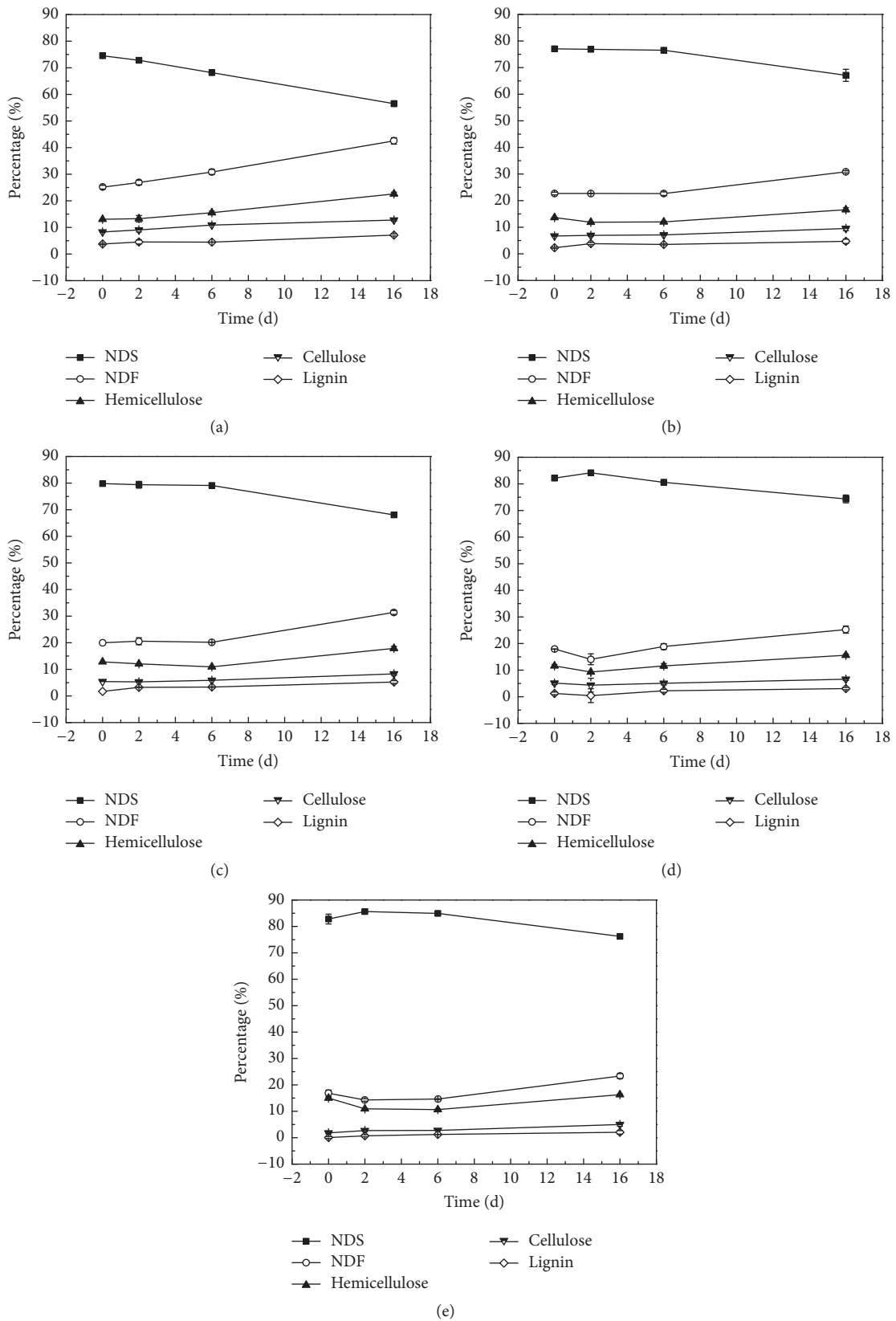
(a)

(b)

(c)

(d)

(e)

FIGURE 7: Evolution of the proportions of biochemical fractions (NDS, NDF, hemicellulose, cellulose, and lignin) in the composting of KW. (a), (b), (c), (d), and (e) represent R1, R2, R3, R4, and R5, respectively.

the CW contribution to the MC and the C/N ratio ($R^2 = 0.83$, $p = 3.33 \times 10^{-16}$) during the composting of KW. Higher C/N ratios could delay the changes in the water states and, therefore, affect the composting performance. For the optimum composting process performance, the initial C/N ratio should be kept in the range 31.00–38.32 to achieve an appropriate lag phase in changes in the water states, which should be around 4 d.

Abbreviations

C_{EX}:   Alkali-extractable organic carbon
C_{HA}:   Humic-acid-like organic carbon
C/N: Ratio of carbon content to nitrogen content
CW: Capillary water
EC: Electrical conductivity
EW: Entrapped water
KW: Kitchen waste
MC: Moisture content
MMLW: Multi-molecular-layer water
NDF: Neutral detergent fiber
NDS: Neutral detergent solute
PHA: Percentage of humic acids
TC: Total carbon
TN: Total nitrogen
VW: Vegetable waste.

Conflicts of Interest

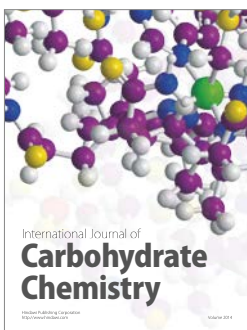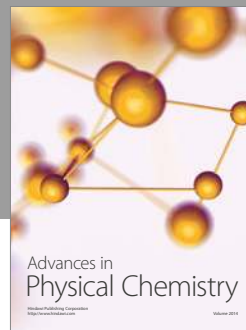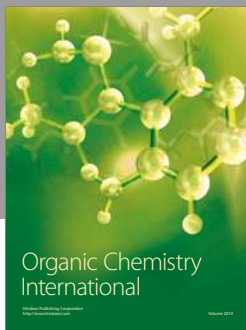The authors declare that they have no conflicts of interest.

Acknowledgments

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