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# Effects of adding bulking agents on the biodrying of kitchen waste and the odor emissions produced

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## ABSTRACT

The effects of adding a bulking agent on the performance and odor emissions (ammonia and eight sulfur-containing odorous compounds) when biodrying kitchen waste were investigated. Three treatments were considered: the addition of either cornstalks (CS) or wood peat (WP) to kitchen waste as a bulking agent before biodrying, and a control treatment (CK). The water-removal rates for CK, CS, and WP treatments were 0.35, 0.56, and 0.43 kg/kg, respectively. Addition of bulking agents to kitchen waste produced less leachate, higher moisture-removal rates, and lower consumption of volatile solids. The CS treatment had the highest biodrying index (4.07), and those for the WP and CK treatments were 3.67 and 1.97, respectively. Adding cornstalks or wood peat decreased NH<sub>3</sub> emissions by 55.8% and 71.7%, respectively. Total sulfur losses were 3.6%–21.6% after 21 days biodrying, and H<sub>2</sub>S and Me<sub>2</sub>SS were the main (>95%) sulfur compounds released. The smallest amounts of sulfur-containing odorous compounds were emitted when cornstalks were added, and adding cornstalks and wood peat decreased total sulfur losses by 50.6%–64.8%.

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## Introduction

In many developing countries (e.g., China), municipal solid waste (MSW) typically has a high water content (up to 75%) because it contains a relatively high proportion (>60%) of kitchen waste (Münich et al., 2006; He et al., 2013). Kitchen waste is organic waste produced by household and restaurant kitchens. Kitchen waste can be separated from other types of MSW in the home or when the MSW is collected. The water content of kitchen waste is a critical parameter when determining the feasibility of various disposal options, such

as direct land application, composting, landfill, and incineration. This high water content lowers the yield of recoverable material and increases the operating costs of combustion. Landfills are the main MSW disposal method in China; they occupy large amounts of land and produce high levels of secondary pollutants, including leachate, greenhouse gases, and odors (Li et al., 2004). Use of thermal drying enables a product with high solid content to be rapidly obtained; however, in most cases, this technique is neither cost-effective nor environmentally friendly because a nonrenewable energy resource is consumed.

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Biodrying is a composting process that has a good potential as a pre-treatment of organic wastes, especially those with high concentrations of organic waste. Composting and other bio-stabilization processes result in complete degradation of easily degradable volatile solids. Microbial metabolism in the biodrying process is similar to that for composting; however, the former is aimed towards water removal, while the latter focuses on the bio-stabilization and maturity of composted materials (Sugni et al., 2005; Bezama et al., 2007; Rada et al., 2007).

The biodrying technique has recently been developed, and the objective of the technique is to remove water from bio-waste with a high water content (Trémier et al., 2009; Velis et al., 2009; Zhang et al., 2009; Rada and Ragazzi, 2015; Tom et al., 2016). Besides having a high water-removal rate, this approach is expected to constrain organic degradation, thereby preserving energy for subsequent utilization, *e.g.*, as residue-derived fuels (Adani et al., 2002) and incineration of the waste (Zhang et al., 2008). It is recognized as a novel and alternative method to treat high-moisture organic wastes due to its relatively short residence time (7–15 days) and high process efficiency (Choi et al., 2001; Velis et al., 2009). As for composting, however, the long residence time (30–50 days) (Velis et al., 2009), high process costs (*e.g.*, 200 USD/dry ton) (Liang et al., 2003) and low product value prevent the wider application of this treatment.

Kitchen waste has a high moisture content, low C/N ratio, and poorly porous biomass matrix, so a bulking agent needs to be added to modify the kitchen waste properties to allow it to be composted or bio-dried. Cornstalks are waste materials that are produced in large amounts in most parts of China. It has been found in many studies that cornstalks are a good bulking agent for composting (Yang et al., 2013; Zhang et al., 2013). Wood peat is rich in carbon and has a high humic acid content and density and a low moisture content. Wood peat mainly comprises lignins, whereas cornstalks contain large amounts of cellulose and hemicellulose. Previous research has focused on the application of this technology for treating dewatered sludge (Xu et al., 2011; Zhao et al., 2011; Cai et al., 2013; Feng et al., 2015). Zhao et al. (2011) reported that when using straw, sawdust, and their combination as the bulking agent; straw has substantial biodegradation potential in the aerobic process, while sawdust has poor capacity to be degraded. Ma et al. (2016) found that sewage sludge mixed with 20% corncobs as the bulking agent resulted in a high water-carrying capacity. Cai et al. (2016) used sawdust as the bulking agent to adjust the moisture content to 62% in sewage sludge biodrying.

Most studies of MSW biodrying have been reported by Zhang et al. (2008, 2011), and a few studies have been focused on biodrying kitchen waste. Zhang et al. (2008), in order to improve the water content reduction and accelerated biodegradation of MSW with high water content, added a hydrolytic stage prior to aerobic degradation, so that more water could be released in the form of leachate, along with hydrolysis or disintegration of volatile solids. Production of leachate is, however, prone to causing secondary environmental pollution and it is very expensive to use physical and chemical processes to treat leachate (Rasool et al., 2016; Wang et al., 2016). This differs from combined hydrolytic-aerobic processes, in that

adding bulking agent can improve the size and number of inter-particle voids in a pile of biodrying waste, increase air permeability, and decrease (or avoid completely) the amount of leachate produced (Yang et al., 2013; Yuan et al., 2015). Furthermore, adding an organic bulking agent that is rich in carbon to kitchen waste biodrying could provide a carbon resource and improve the calorific value of the final biodrying product (Rada et al., 2009).

It is crucial that we understand how to effectively and economically use the energy generated during biodrying to remove as much water as possible in as little time as possible under optimal conditions (Velis et al., 2009). The mismanagement of a biodrying process can cause odorous gases to be emitted, causing secondary environmental pollution and negatively affecting the wellbeing of the workers at the biodrying facility, the quality of life of people living near the facility, and environmental quality. Ammonia (NH<sub>3</sub>) and volatile sulfur compounds (VSCs) have been found to be the predominant odorants emitted when organic waste is composted (Burgess et al., 2001; Wu et al., 2010; Shen et al., 2011). It has previously been found that 16%–74% of the initial total nitrogen (TN) content is lost during composting (Raviv et al., 2002; Ren et al., 2010) and that 9.6%–46% of the initial TN content is lost as NH<sub>3</sub> (Jiang et al., 2011; Luo et al., 2014). It has been found that reduced sulfur compounds have low detection thresholds and strong odors (Goldstein, 2006; Yu et al., 2007). These sulfur compounds include hydrogen sulfide (H<sub>2</sub>S), carbon disulfide (CS<sub>2</sub>), dimethyl sulfide (Me<sub>2</sub>S), methyl mercaptan (MeSH), and dimethyl disulfide (Me<sub>2</sub>SS) (Delgado-Rodríguez et al., 2012; Wang et al., 2012). The concentrations of NH<sub>3</sub>, H<sub>2</sub>S, MeSH, Me<sub>2</sub>S, Me<sub>2</sub>SS, and CS<sub>2</sub> in waste air produced by units that emit odorous gases are limited by the Chinese Ministry of Environmental Protection under standard GB 14554–1993 (Chinese standard, 1993) because these compounds are malodorous, cause health problems, and play strong roles in global climate change (Yi et al., 2008; Caro and Gallego, 2009). VSCs produced during the composting of mixed MSW and kitchen waste have been measured (Wu et al., 2010; Shen et al., 2012). It has been suggested that odorous sulfur-containing chemicals are produced in anaerobic parts of composting material (Schlegelmilch et al., 2005; Hort et al., 2013). Adding a bulking agent will change the C/N ratio, moisture content, and porosity of the composting material, and therefore affect the conversion of organic matter, the transfer of oxygen, and the production and release of odors. Shao et al. (2014) found that adding rice straw to the organic fraction of MSW could significantly reduce the malodorous sulfur compound emissions. He et al. (2010) found that the largest amounts of VSCs were released in the first 4 days of a biodrying process and that the dominant components were Me<sub>2</sub>SS and Me<sub>2</sub>S. Cornstalks have been widely used as a composting bulking agent to improve the compost maturity and decrease the NH<sub>3</sub> production (Jiang et al., 2011; Yang et al., 2013; Yuan et al., 2015) and VSC emission (Zhang et al., 2013). Zhang et al. (2013) reported that addition of dry cornstalks at a mixing ratio of 4:1 (wet weight) could reduce the VSCs emissions by 66.8% and avoid leachate during kitchen waste treatment. Wood peat has been used widely as a bedding or filter material to remove ammonia from solid waste, because it has a high cation exchange capacity and can adsorb a wide

range of cations. Compared with other bedding materials such as cornstalks and wood shavings, woody peat can adsorb four times more ammonia in the manure (Kemppainen, 1987). Peat used in composting could reduce 25%–60% of  $\text{NH}_3$  emissions, with high ammonia adsorption capacity (Witter and Kirchmann, 1989).

An extensive literature search concluded that most studies of biodrying MSW have been focused on removing water, the degradation of organic material, and the calorific value of the product (Adani et al., 2002; Sugni et al., 2005; Bilgin and Tulun, 2015). Few studies have involved determining the water-removal capacities, indices of biodrying processes, and contributions of the degradation of specific biochemical components to the total loss of organic material. Furthermore, most studies of odor emissions have been focused on the composting of organic waste, but few studies have been performed on odor emissions during the biodrying of kitchen waste. Therefore, in the study described here, the biodrying performance and odor emissions during the biodrying of kitchen waste were comprehensively evaluated. The water-removal capacity, biodrying index, and the contributions of the degradation of specific biochemical components to the total loss of organic matter were determined. Emissions of ammonia and eight odorous sulfur compounds were measured and the effects of adding a bulking agent on their emissions were determined during the biodrying of kitchen waste.

## 1. Materials and methods

### 1.1. Materials and experimental set-up

The kitchen waste was manually sorted from MSW provided by the Majialou MSW transfer station (Beijing, China). The kitchen waste consisted of, by wet weight, 53% uneaten vegetables, 27% fruit peel, 17% uneaten portions of meals, and 6% leaves. Cornstalks were obtained from a research station at the China Agricultural University. The cornstalks were passed through a cutting mill to produce pieces 1–5 cm in size. Wood peat was obtained from Indonesia and was provided by Sino-View International Co. Ltd. (Beijing, China). The properties of the raw materials are shown in Table 1.

Each trial was performed in a laboratory column reactor (60 L in volume, 0.6 m high, 0.36 m inner diameter) made of stainless steel (Fig. 1). Each vessel was insulated and had two layers of stainless steel to minimize heat loss. A stainless steel cap was fitted to the top of each reactor to allow the reactor to be filled and emptied. A 3-mm stainless steel grid was installed at the bottom of each reactor to support the composting bed and to ensure that the gases added were uniformly distributed. Two holes in the bottom of each reactor allowed the reactor to be aerated (the aeration gas was added using a controllable aquarium pump) and the leachate to drain away. Each reactor had three 5-cm diameter sampling points, 0.2, 0.4, and 0.6 m from the bottom. Each sampling point was plugged when not in use. Two holes in the lid of each vessel allowed a temperature sensor to be inserted and the gas within the vessel to be sampled. An exhaust port (50-mm inner diameter) in the lid of each vessel was connected to a condenser using plastic piping. A jar at the bottom of the

**Table 1 – Physical and chemical characteristics of the raw materials.**

Materials	Kitchen waste	Cornstalks	Wood peat
Moisture (%) <sup>*</sup>	77.47 ± 0.33	7.43 ± 0.11	13.19 ± 0.23
Bulk density (kg·m <sup>-3</sup> ) <sup>*</sup>	699 ± 22.42	162 ± 8.73	814 ± 6.91
TC (%) <sup>**</sup>	36.29 ± 1.14	41.72 ± 0.10	52.14 ± 0.18
TN (%) <sup>**</sup>	1.70 ± 0.02	1.21 ± 0.01	0.65 ± 0.01
TS (%) <sup>**</sup>	0.48 ± 0.03	0.38 ± 0.04	0.38 ± 0.01
C/N	21.37	34.59	80.34
Volatile solids (VS) (%) <sup>**</sup>	70.55 ± 0.46	91.3 ± 0.38	94.7 ± 0.10
Amylums (%) <sup>**</sup>	4.64 ± 0.43	3.45 ± 0.29	0.27 ± 0.21
Lipids (%) <sup>**</sup>	13.78 ± 0.21	10.89 ± 0.14	14.40 ± 0.09
Proteins (%) <sup>**</sup>	12.50 ± 0.26	7.21 ± 0.04	3.55 ± 0.02
Cellulose (%) <sup>**</sup>	16.78 ± 0.30	30.59 ± 1.31	0.00
Hemicellulose (%) <sup>**</sup>	6.84 ± 0.16	20.20 ± 0.35	0.00
Lignins (%) <sup>**</sup>	18.48 ± 0.45	19.39 ± 0.19	72.36 ± 0.92

TN: total nitrogen; TC: total carbon; TS: total sulfur.

<sup>\*</sup> Wet weight basis.

<sup>\*\*</sup> Dry weight basis.

condenser allowed condensed water to be collected. The experimental set-up has been used in previous studies (Guo et al., 2012; Shen et al., 2011).

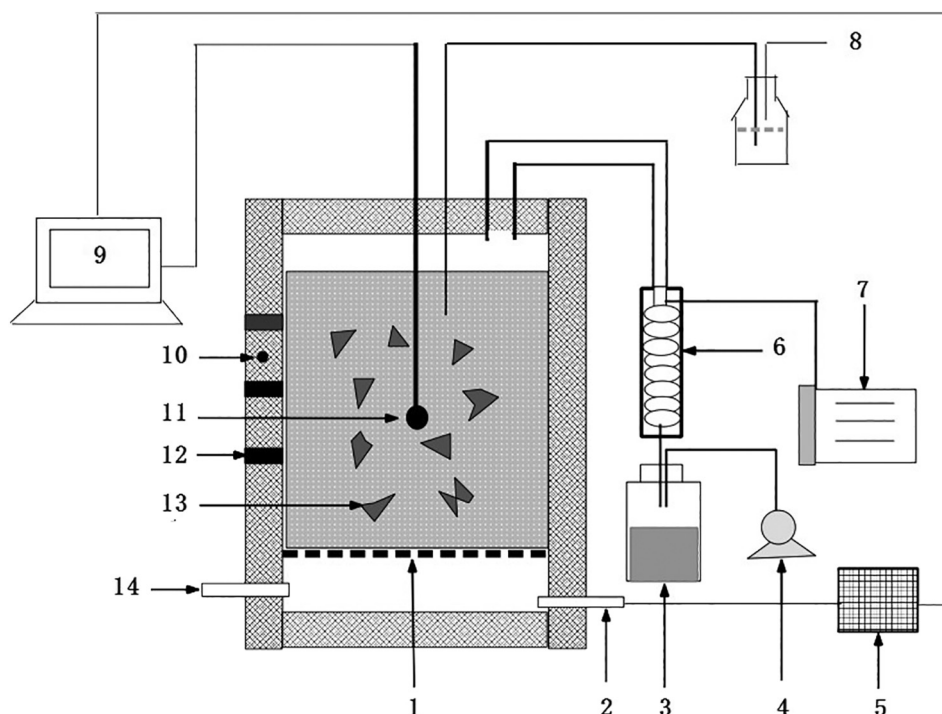
Three biodrying trials were conducted. The control treatment, labeled CK here, contained 100% kitchen waste (i.e., without any bulking agent added), one treatment (labeled CS) contained 15% (by wet mass) cornstalks and 85% kitchen waste, and one treatment (labeled WP) contained 15% (by wet mass) wood peat and 85% kitchen waste.

Each biodrying trial lasted for 21 days. A forced-draft aeration system was used. Each system was continuously aerated at a rate of 0.3 L/(kg·min) (calculated using the dry mass of material in the reactor). The waste in each reactor was manually turned every 3 days. The temperature in each vessel was recorded using the C-LGX program (Scan-2000x, Hongyuanpengao, Beijing, China).

### 1.2. Sample collection and analytical methods

The leachate and condensate produced were collected and weighed every day, and the masses of the vessels were recorded at the same time. A sample of about 200 g of the solid material was taken from each vessel at the beginning and end of the composting process and after each turning procedure had been performed. A subsample of approximately 30 g was taken from each sample and the moisture content measured immediately. The remaining sample was divided into two parts. One part was stored at 4°C for further analysis, and the other was air-dried, ground, and passed through a 1 mm sieve. The moisture content of each wet sample was determined in triplicate. The total nitrogen (TN), total carbon (TC), total sulfur (TS), and volatile solid (VS) contents and biochemical composition (amylums, proteins, lipids, cellulose, hemicellulose, and lignins) of each dried and ground sample were determined in triplicate.

The moisture content of a sample was determined by heating triplicate subsamples to 105°C until each subsample reached a constant weight. The VS content was determined by heating triplicate subsamples to 550°C until each sample



**Fig. 1 – Diagram of a biodrying reactor. 1 Lattice cell; 2 Gas flowmeter; 3 Jar for collecting condensate; 4 Air pump; 5 Automatic ventilation control system; 6 Condenser pipe; 7 Refrigerator; 8 Gas outlet sampling port; 9 Automatic control system; 10 Heat insulating layer; 11 Temperature sensor; 12 Solid sampling port; 13 Biodrying material samples collected; 14 Leachate sampling port.**

reached a constant weight. The neutral detergent fiber, acid detergent fiber, and ash contents of each sample were determined and used to calculate the cellulose, hemicellulose, and lignin contents (Goering and van Soest, 1970). The amylum content of a sample was determined by digesting the air-dried sample in ether, ethanol, and boiling HCl solution (6 mol/L) in sequence, then titrating the solution with alkaline copper tartrate (Horwitz, 2005). The lipid content of a sample was determined gravimetrically after Soxhlet extracting the sample with petroleum ether (Nielsen, 2002). The protein content was determined from the Kjeldahl nitrogen content, which was multiplied by 6.25 to give the protein content (APHA, 1998). The TC, TN, and TS contents were measured using an elemental analyzer (Elementar Analysensysteme, Hanau, Germany).

The ventilation flow in the air inlet and gas outlet of reactor was measured twice each day (6:00–7:00 and 18:00–19:00) by a gas flowmeter. The average ventilation flow obtained from these two measurement times was assumed to be representative for the whole day. The total gas outlet volume was calculated according to the ventilation flow in the gas outlet and ventilation time. The biodrying reactor had a good degree of leakproofness, so the gas flow in the air inlet and gas outlet of the reactor basically stayed the same. The same calculation method has been used in previous studies (Shen et al., 2011; Jiang et al., 2011; Yuan et al., 2015). A gas sample from each reactor was collected and analyzed each day.  $\text{NH}_3$  in the gas sample was trapped in boric acid in a wash bottle and titrated against 0.1 mol/L  $\text{H}_2\text{SO}_4$ . The total odor emission each day was calculated by multiplying the ventilation volume by the representative odor concentration

during that day. Cumulative odor emissions were calculated by summing the odor emissions for each day. A Tedlar bag was connected to the exhaust port, flushed three times, and then filled with gas for 1 min. The  $\text{O}_2$  concentration in the sample bag was measured using a biogas monitor (BIOGAS-5000, Geotech, UK), then the sample bag was connected to a gas chromatograph (GC-A90, Echrom, China) to allow the concentrations of sulfur-containing odorous compounds to be determined. The gas chromatograph had been calibrated and met the analysis requirements for sulfur compounds. The gas chromatograph was equipped with a capillary column (Gas pro, Agilent, USA) and a flame photometric detector. All of the gas chromatograph tubes and fittings that came into contact with the sample gas were made of polytetrafluoroethylene (the sample gas came into contact with no metal) and a large amount of each gas sample was pumped through the system to minimize adsorption and ensure that the sulfur-containing odorous compound measurements were accurate. The gas chromatograph oven temperature started at 60°C, then increased at 20°C/min to 200°C, then remained at 200°C for 10 min. The carrier gas was He, and the flow rate was 3 mL/min. The gas chromatograph was calibrated using standard gases prepared by a commercial gas supplier (Haipu, Beijing). Three standard gases were used. The first contained 5-ppm  $\text{Me}_2\text{S}$ , the second 5-ppm diethyl sulfide and 5-ppm  $\text{Me}_2\text{S}$ , and the third 5-ppm carbonyl sulfide, 10-ppm  $\text{CS}_2$ , 40-ppm  $\text{H}_2\text{S}$ , 5-ppm  $\text{MeSH}$ , and 5-ppm ethyl mercaptan. The same sulfur standard gases and gas chromatograph were used in a previous study (Zang et al., 2016). The results were analyzed using Echrom Chem Lab software version 1.0.2 (Echrom, China). The detection limits were on the order of 100 ppb (ppbv) by



volume, and the precision of repeated analyses was on the order of  $\pm 5\%$ .

### 1.3. Statistical analysis

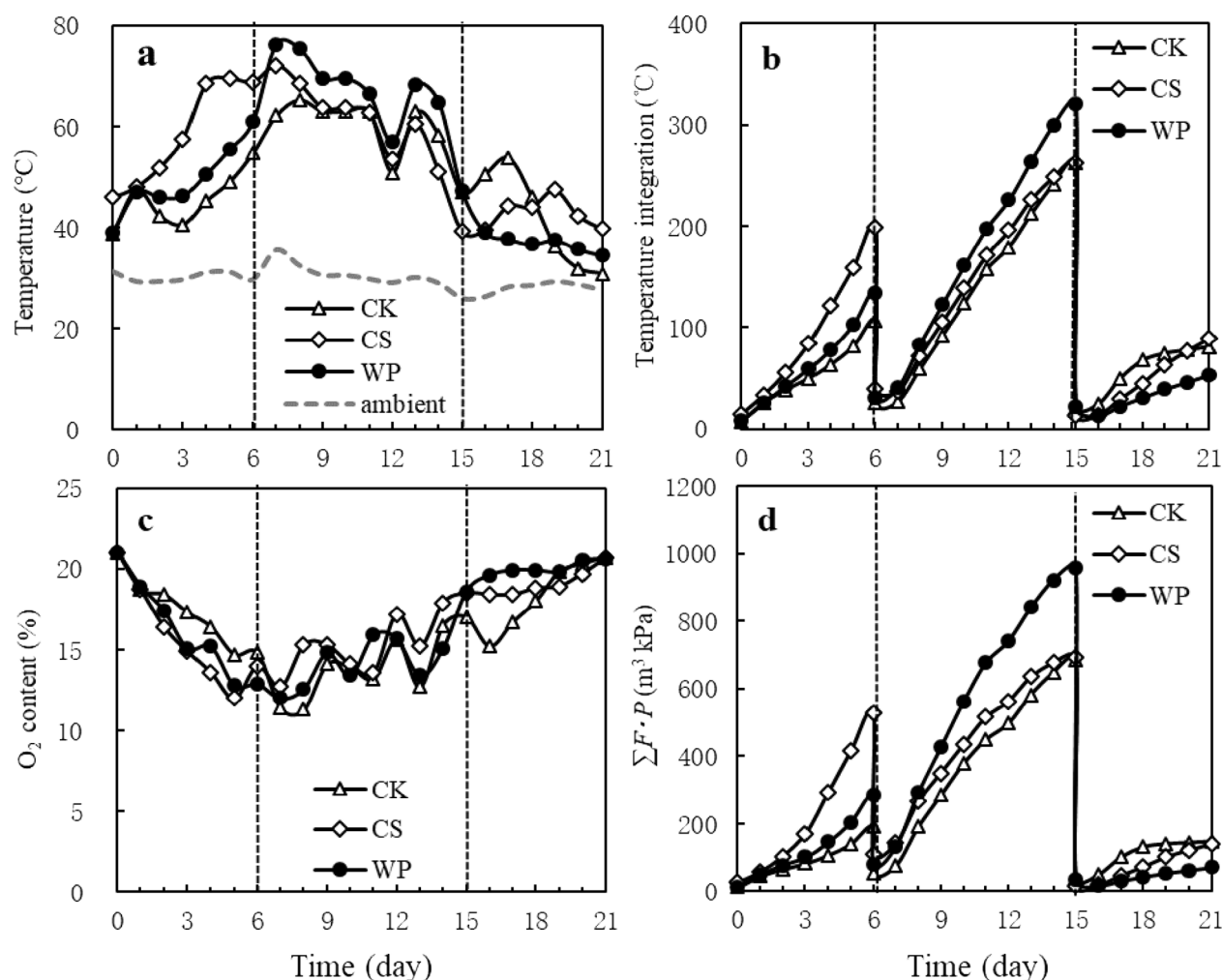
The mean value and standard deviation of three replicates of each treatment were reported. SAS 8.2 for Windows (SAS Institute, Cary, NC, USA) was used for all of the statistical analyses.

## 2. Results and discussion

### 2.1. Changes in the $O_2$ concentration and temperature during biodrying

The temperature is the most important factor affecting the degradation of organic material and the evaporation of water during biodrying. The temperatures of the reactors each day during the study are shown in Fig. 2a. The temperature

integration (TI) index was used (the accumulated daily difference between the waste and ambient temperatures) to clearly indicate the temperature differences between the treatments (Zhang et al., 2008) (Fig. 2b). The temperature of a biodrying pile will increase because of organic matter being degraded by aerobic microorganisms consuming oxygen. Similar to the composting of organic material, feedstock being bio-dried will go through three degradation phases, the mesophilic, thermophilic, and curing phases. The thermophilic phase ( $>50^\circ\text{C}$ ) was reached on day 6 of the CK treatment, day 2 of the CS treatment, and day 4 of the WP treatment. The thermophilic phase was entered earlier and lasted longer in the CS and WP treatments than in the CK treatment. This was probably because adding cornstalks to kitchen waste decreased the moisture content and increased the free air pore volume in the compost, both of which would have been conducive to organic matter decomposition. The high moisture content, low porosity, and low pH of the pure kitchen waste in the early stages of the biodrying process would not have been conducive to organic matter degradation. Similar results have been found



**Fig. 2** – Temporal changes in the temperature,  $O_2$  concentration, and water-removal capacity achieved through ventilation ( $\Sigma F \cdot P$ ) during the biodrying processes. (a) daily temperature, (b) temperature integration, (c)  $O_2$  concentration, (d)  $\Sigma F \cdot P$  (the product of the air flow rate and the saturated vapor pressure of the ventilated air). Standard deviations of mean values ( $n = 3$ ) of temperature (a) and oxygen content (c) were in the range of  $0.1\text{--}5.8^\circ\text{C}$  and  $0\text{--}3.6\%$ , respectively. CK: control; CS: 15% cornstalks added; WP: 15% wood peat added.

in previous studies of kitchen waste composting (Yang et al., 2013; Yuan et al., 2015), which indicated that adding a bulking agent could create advantages for microbial activity and promote the degradation of organic matter. The temperatures of the CS and WP treatments were not significantly different ( $p = 0.284$ ), but both were significantly higher than the temperature of the CK treatment ( $p = 0.014$  for the CS treatment and  $p = 0.050$  for the WP treatment).

The CS treatment had the highest TI value throughout the biodrying process (the CK, CS, and WP treatment TI values were 449.9, 549.3, and 507.7°C, respectively). The highest TI values were found between days 0 and 6 for the CS treatment, between days 6 and 15 for the WP treatment, and from day 15 onward for the CK treatment.

The  $O_2$  concentration significantly negatively correlated with the temperature in all of the treatments ( $R = -0.823$  to  $-0.922$ ,  $p = 0.000$ ). The  $O_2$  concentration decreased rapidly in the first five days of the biodrying process in all of the treatments, then slowly fluctuated or increased after five days (Fig. 2c).

The water-removal capacity through ventilation was determined using the  $\Sigma F \cdot P$  index (Fig. 2d) (Zhang et al., 2008). Similar to the TI results, the highest  $\Sigma F \cdot P$  values were found between days 0 and 6 for the CS treatment, between days 7 and 15 for the WP treatment, and between days 16 and 21 for the CK treatment. The CS treatment had the highest  $\Sigma F \cdot P$  value (the  $\Sigma F \cdot P$  values for the CK, CS, and WP treatments were 1165.6, 1455.6, and 1293.2  $m^3 \cdot kPa$ , respectively).

## 2.2. Water loss and organic losses during biodrying

The CS treatment gave the highest water-removal rate through evaporation for the whole biodrying process (0.56 kg/kg); the WP treatment gave a lower rate (0.43 kg/kg), and the CK treatment gave the lowest rate (0.36 kg/kg) (Table 2). No leachate was produced by the CS treatment, whereas the

leachate production rates were 0.04 and 0.16 kg/kg for the WP and CK treatments, respectively. The CK, CS, and WP treatment moisture contents decreased by 15.2%, 28.0%, and 20.3%, respectively, during the biodrying process, and the final moisture contents were 65.98%, 46.94%, and 55.79%, respectively. Statistical analyses showed that adding a bulking agent significantly affected the moisture content ( $p = 0.000$ ). Different bulking agents have largely been used to improve the performance and maturity of waste composting. Guo et al. (2012) found that the initial C/N ratio had the main influence on the maturity of the final compost, compared with the factors of aeration rate and moisture content. Therefore, the main aim of adding bulking agents during composting was to adjust to an appropriate C/N ratio. However, bio-drying technology is aimed at removing water, mainly as vapor, by adequate ventilation combined with the high temperature resulting from organics degradation (Sugni et al., 2005). Adding bulking agents had a significant effect on the water removal of bio-drying through modifying the moisture contents and free air pore volume.

The VS contents decreased by 26.8%, 19.4%, and 15.1% for CK, CS, and WP treatments, respectively, during the biodrying process. Adding a bulking agent gave a higher VS content at the end of the biodrying process, and less organic matter was degraded in the treatments with bulking agents added than in the CK treatment. The WP treatment gave the highest final VS content, because this treatment had wood peat added. Wood peat has a high lignin content, making it more difficult to degrade than materials with lower lignin contents. There were significant differences between the VS contents for the three treatments ( $p = 0.000$ ).

The aim of the biodrying process is to remove water and consume only small amounts of organic material to give a final product with a low moisture content and high calorific value. The biodrying index (I) was defined as the ratio of water lost to organic material lost, and the index was used to indicate the performance of a biodrying system. Only water

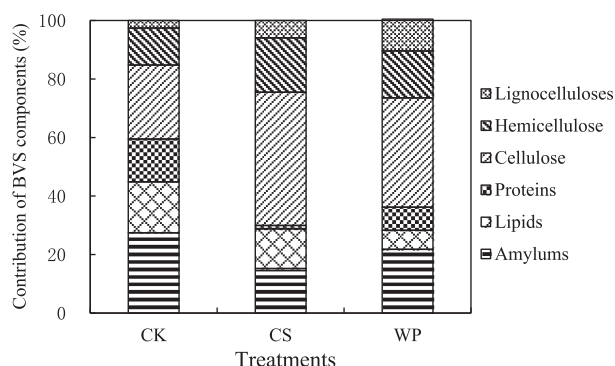
**Table 2 – Biochemical component contents before and after the biodrying processes.**

Treatment	Biodrying time	CK	CS	WP
Moisture content (%) <sup>*</sup>	Initial	77.84 ± 0.97	65.18 ± 0.91	69.98 ± 0.26
	Final	65.98 ± 1.54	46.94 ± 1.76	55.79 ± 0.38
Leachate (kg/kg) <sup>*</sup>	Final	0.16	0.00	0.04
Evaporated water loss (kg/kg) <sup>*</sup>	Final	0.35	0.56	0.43
Volatile solids (VS) (%) <sup>**</sup>	Initial	70.55 ± 0.46	72.09 ± 0.10	74.04 ± 0.30
	Final	51.62 ± 0.66	58.14 ± 1.19	62.85 ± 1.76
Amylums (%) <sup>**</sup>	Initial	10.64 ± 0.24	7.07 ± 0.18	7.01 ± 0.09
	Final	1.44 ± 0.02	2.94 ± 0.03	2.64 ± 0.02
Lipids (%) <sup>**</sup>	Initial	13.78 ± 0.41	13.41 ± 0.53	11.37 ± 0.29
	Final	10.74 ± 0.17	11.68 ± 0.23	11.28 ± 0.46
Proteins (%) <sup>**</sup>	Initial	12.50 ± 0.36	9.64 ± 0.21	10.72 ± 0.34
	Final	10.37 ± 0.09	11.84 ± 0.16	10.39 ± 0.11
Celluloses (%) <sup>**</sup>	Initial	16.78 ± 0.24	23.03 ± 0.47	17.29 ± 0.30
	Final	11.11 ± 0.14	11.24 ± 0.08	10.67 ± 0.31
Hemicelluloses (%) <sup>**</sup>	Initial	6.84 ± 0.06	9.94 ± 0.11	5.30 ± 0.10
	Final	3.40 ± 0.05	5.29 ± 0.03	2.13 ± 0.01
Lignins (%) <sup>**</sup>	Initial	11.48 ± 0.15	15.25 ± 0.20	32.68 ± 0.34
	Final	14.84 ± 0.21	17.13 ± 0.28	35.00 ± 0.30

CK: control; CS: 15% cornstalks added; WP: 15% wood peat added.

<sup>\*</sup> Dry weight basis.

<sup>\*\*</sup> Wet weight basis.



**Fig. 3 – Contributions of the degradation of specific biochemical components to the total loss of organic material. BVS: biodegradable volatile solids.**

lost through evaporation was included (i.e., leachate was not included). The CS treatment had the highest  $I$  value throughout the biodrying process (4.07), and the WP and CK treatments  $I$  values were 3.67 and 1.97, respectively.

The degradable components of organic waste contain amylums, lipids, proteins, cellulose, hemicellulose, and lignins. The amylum, cellulose, and hemicellulose contents decreased strongly in all of the treatments, but the lipid and protein contents changed little. Only the lignin contents had increased at the end of all of the biodrying treatments. This would have been because lignins are recalcitrant and so are degraded more slowly than other components.

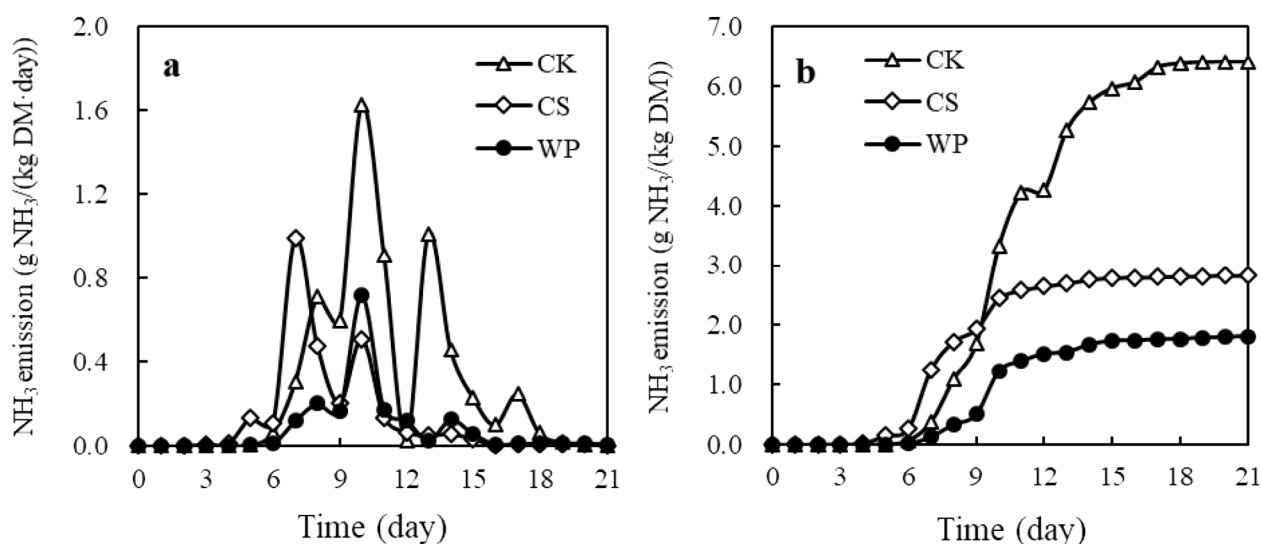
The contributions of the degradation of specific biochemical components to total organic losses are shown in Fig. 3. The main contributors to the loss of organic material in the CK treatment came from the degradation of amylums (27.45% of the total loss), cellulose (25.3%), and lipids (17.44%), which together accounted for 70.2% of the total loss of organic matter. Cellulose (44.98% of the total organic matter lost), hemicellulose (18.39%), and amylums (15.01%) were the main

contributors to the loss of organic material in the CS treatment. Cellulose, hemicellulose, and amylums were also the main contributors to the loss of organic material in the WP treatment, accounting for 75.0% of the lost organic material. It is worth mentioning that the loss of lignins contributed much more to the total loss of organic material in the WP treatment than in the other two treatments.

## 2.3. Odor emissions

### 2.3.1. Ammonia emissions

Emissions of  $\text{NH}_3$  mainly occurred during the thermophilic phase in all of the treatments, probably because organic nitrogen would have been degraded quickly to give inorganic nitrogen during that phase.  $\text{NH}_3$  emissions were significantly positively correlated with the temperature in all of the treatments ( $R = 0.636\text{--}0.787$ ,  $p = 0.000$ ). The  $\text{NH}_3$  emission rates during the biodrying process were similar to  $\text{NH}_3$  emission rates that have been found during composting (Yang et al., 2013; Yuan et al., 2016).  $\text{NH}_3$  emissions peaked at 1.63 g/(kg-day) on a dry matter basis on day 10 for the CK treatment, 0.99 g/(kg-day) on day 7 for the CS treatment, and 0.72 g/(kg-day) on day 10 for the WP treatment. After day 18,  $\text{NH}_3$  emissions from all three treatments gradually decreased as the biodrying temperature decreased (Fig. 4a). The cumulative  $\text{NH}_3$  emissions for the whole biodrying process for the CK, CS, and WP treatments were 6.40, 2.83, and 1.81 g/kg, respectively (Fig. 4b). Adding wood peat decreased the amount of  $\text{NH}_3$  emitted by 71.7%. This could be because of the high humic acid content of wood peat, meaning that ammonium humate would have been produced during the biodrying process, decreasing the amount of  $\text{NH}_4^+$  present and therefore decreasing the amount of  $\text{NH}_3$  that could be emitted. Wood peat could also physically absorb more  $\text{NH}_3$  than kitchen waste or cornstalks, and this would also have decreased the amount of  $\text{NH}_3$  emitted during the WP treatment. Similar results were found in a study by Witter and Kirchmann (1989), in which the absorption of  $\text{NH}_3$  by wood peat was found to be



**Fig. 4 – (a) Emission rates and (b) cumulative emissions of  $\text{NH}_3$  during the biodrying processes. Standard deviations of mean values ( $n = 3$ ) of emission rates (a) and cumulative emission (b) of  $\text{NH}_3$  in the range of 0.02–0.17 g  $\text{NH}_3\text{-N}/(\text{kg DM}\cdot\text{day})$  and 0.02–0.39 g  $\text{NH}_3\text{-N}/(\text{kg DM}\cdot\text{day})$ . DM: dry matter.**

the main reason for wood peat decreasing  $\text{NH}_3$  emissions. Adding cornstalks to the kitchen waste decreased  $\text{NH}_3$  emissions by 55.8%, and this was probably because of the low bulk density of the cornstalks and the relatively low TN content of the CS treatment material. There were no significant differences between the amounts of  $\text{NH}_3$  emitted during the CS and WP treatments ( $p = 0.489$ ), but the amounts of  $\text{NH}_3$  emitted during both treatments were significantly different from the amount of  $\text{NH}_3$  emitted during the CK treatment ( $p = 0.018$  for the CS treatment and  $p = 0.003$  for the WP treatment).

### 2.3.2. Production of VSCs

The VSCs of  $\text{H}_2\text{S}$ ,  $\text{Me}_2\text{SS}$ ,  $\text{Me}_2\text{S}$ , and  $\text{CS}_2$  were detected during all of the treatments. Zhang et al. (2013) found the same sulfur-containing odorous compounds when MSW was composted. Diethyl sulfide and ethyl mercaptan were not found during any of the treatments. MeSH was only found on day 7 of the CK treatment, and the concentration was 4.08 ppm. MeSH can be converted into  $\text{Me}_2\text{SS}$  abiotically through dehydration and combination, and this could be why the MeSH concentration was low compared with the  $\text{Me}_2\text{SS}$  concentration (Higgins et al., 2006). MeSH was found to be the dominant odorous compound when pig manure was composted (Blazy et al., 2014). Zhang et al. (2013) detected MeSH throughout the period MSW was composted, but Zang et al. (2016) did not find any MeSH being released when pig manure was composted with a high aeration rate. The amounts of MeSH emitted during our study may have been influenced by the aeration rate, which was higher in our study than in the studies performed by Zhang et al. (2013) and Zang et al. (2016). Adding cornstalks or wood peat may be an effective way of controlling MeSH emissions. Carbonyl sulfide was only continually detected during the thermophilic phase (days 6 to 17) of the CK treatment, and it was found at a low concentration (<0.563 ppm).  $\text{CS}_2$  was detected during all of the treatments, but at extremely low concentrations (<0.1 ppm).  $\text{CS}_2$  was found on four occasions during the CK treatment, and the highest  $\text{CS}_2$  concentration (0.099 ppm) was found on day 10.  $\text{CS}_2$  was found on only one occasion during the CS treatment (<0.1 ppm on day 7) and on only one occasion during the WP treatment (<0.1 ppm on day 7).

The predominant sulfur compounds that were emitted were  $\text{H}_2\text{S}$ ,  $\text{Me}_2\text{SS}$ , and  $\text{Me}_2\text{S}$ . Shao et al. (2014) also found that more  $\text{H}_2\text{S}$ ,  $\text{Me}_2\text{SS}$ , and  $\text{Me}_2\text{S}$  than other sulfur compounds were emitted when MSW was composted.  $\text{H}_2\text{S}$  emissions mainly occurred during the thermophilic phase and peaked between days 6 and 7 (Fig. 5a). The amount of  $\text{H}_2\text{S}$  emitted during the CS treatment was 93% lower than the amount emitted during the CK treatment, probably because the cornstalks provided inter-particle voids and air spaces in the material being bio-dried and improved the regulation of the water content. There was a significant difference between the amounts of  $\text{H}_2\text{S}$  produced during the CK and CS treatments ( $p = 0.011$ ). The amount of  $\text{H}_2\text{S}$  emitted was 53% lower during the WP treatment than during the CK treatment, possibly because of the high adsorption capacity of wood peat. Like  $\text{H}_2\text{S}$ ,  $\text{Me}_2\text{SS}$  emissions mainly occurred during the thermophilic phase (Fig. 5c). The temperature and amount of  $\text{Me}_2\text{SS}$  produced were significantly positively correlated for all of the treatments ( $R = 0.563$  to  $0.707$ ,  $p = 0.012$ ). Adding a bulking agent to the kitchen waste decreased the amount of  $\text{Me}_2\text{SS}$  emitted, by 92% for cornstalks

and 71% for wood peat. The amounts of  $\text{Me}_2\text{SS}$  emitted during the CS and WP treatments were not significantly different ( $p = 0.525$ ), but the amounts emitted during both treatments were significantly different from the amount emitted during the CK treatment ( $p = 0.008$  for the CS treatment and  $p = 0.037$  for the WP treatment). Relatively little  $\text{Me}_2\text{S}$  was emitted during each treatment, and the cumulative  $\text{Me}_2\text{S}$  emissions during the CK, CS, and WP treatments were 0.10, 0.02, and 0.04 g/kg, respectively. The amounts of  $\text{Me}_2\text{S}$  produced during the CS and WP treatments were 78% and 59% less, respectively, than what was produced during the CK treatment. There was no significant difference between the amounts of  $\text{Me}_2\text{S}$  emitted during the CS and WP treatments ( $p = 0.233$ ), but the amounts of  $\text{Me}_2\text{S}$  emitted during both treatments were significantly different from the amount of  $\text{Me}_2\text{S}$  emitted during the CK treatment ( $p = 0.000$  for both the CS and WP treatments).

It has been suggested that high VSC emissions occur during food waste composting when high levels of microbial activity occur and the compost temperature is high, causing  $\text{O}_2$  to be depleted (D'Imporzano et al., 2008; Hanajima et al., 2010; Hort et al., 2013). Adding a bulking agent can decrease VSCs emissions by improving the distribution of  $\text{O}_2$  in the composting mixture and decreasing the extent of anaerobic sites within the mixture.

### 2.3.3. Carbon, nitrogen, and sulfur balances

The initial and final compositions of the compost mixtures and the total carbon, TN, and total sulfur mass balances at the end of each composting period are shown in Table 3. Less dry matter was lost in the CS treatment than in the CK treatment, and the least dry matter was lost in the WP treatment. The loss of total carbon followed a similar pattern to the loss of dry matter. Between 10.5% and 26.7% of the initial TN content was lost during the biodrying process, and 7.2%–19.5% of the initial TN was lost as  $\text{NH}_3$ .  $\text{NH}_3$  was the main form in which nitrogen was lost, accounting for 47%–77% of the TN losses. Adding cornstalks decreased the amount of TN that was lost by 60%, and adding wood peat decreased the amount of TN that was lost by 43%. Similar results were found by Jiang et al. (2013) when pig feces were composted and by Yuan et al. (2015) when kitchen waste was composted. Adding cornstalks decreased the amount of total sulfur lost by 65%, and adding wood peat decreased the amount of total sulfur lost by 51%.

The sulfur lost through carbonyl sulfide,  $\text{CS}_2$ ,  $\text{H}_2\text{S}$ , MeSH, ethyl mercaptan, diethyl sulfide,  $\text{Me}_2\text{S}$ , and  $\text{Me}_2\text{SS}$  emissions accounted for 3.6%–21.6% of the total initial sulfur contents of the feedstocks (Table 4) and 24.2%–53.7% of the total sulfur that was lost.  $\text{H}_2\text{S}$  and  $\text{Me}_2\text{SS}$  were the predominant sulfur compounds that were emitted (accounting for >95% of the sulfur lost as all eight sulfur-containing odorous compounds). The third most important VSC produced was  $\text{Me}_2\text{S}$ , which accounted for 3.07%–4.96% of the total VSCs that were released. Different amounts of VSCs have been found to be produced during organic material composting in previous studies. Zang et al. (2016) found that  $\text{Me}_2\text{S}$  and  $\text{Me}_2\text{SS}$  were the main VSCs produced when pig manure was composted, and Zhang et al. (2011) found that MeSH was the main VSC produced when food waste was composted. Our results were similar to the results found in a study performed by Zhang et al. (2013).



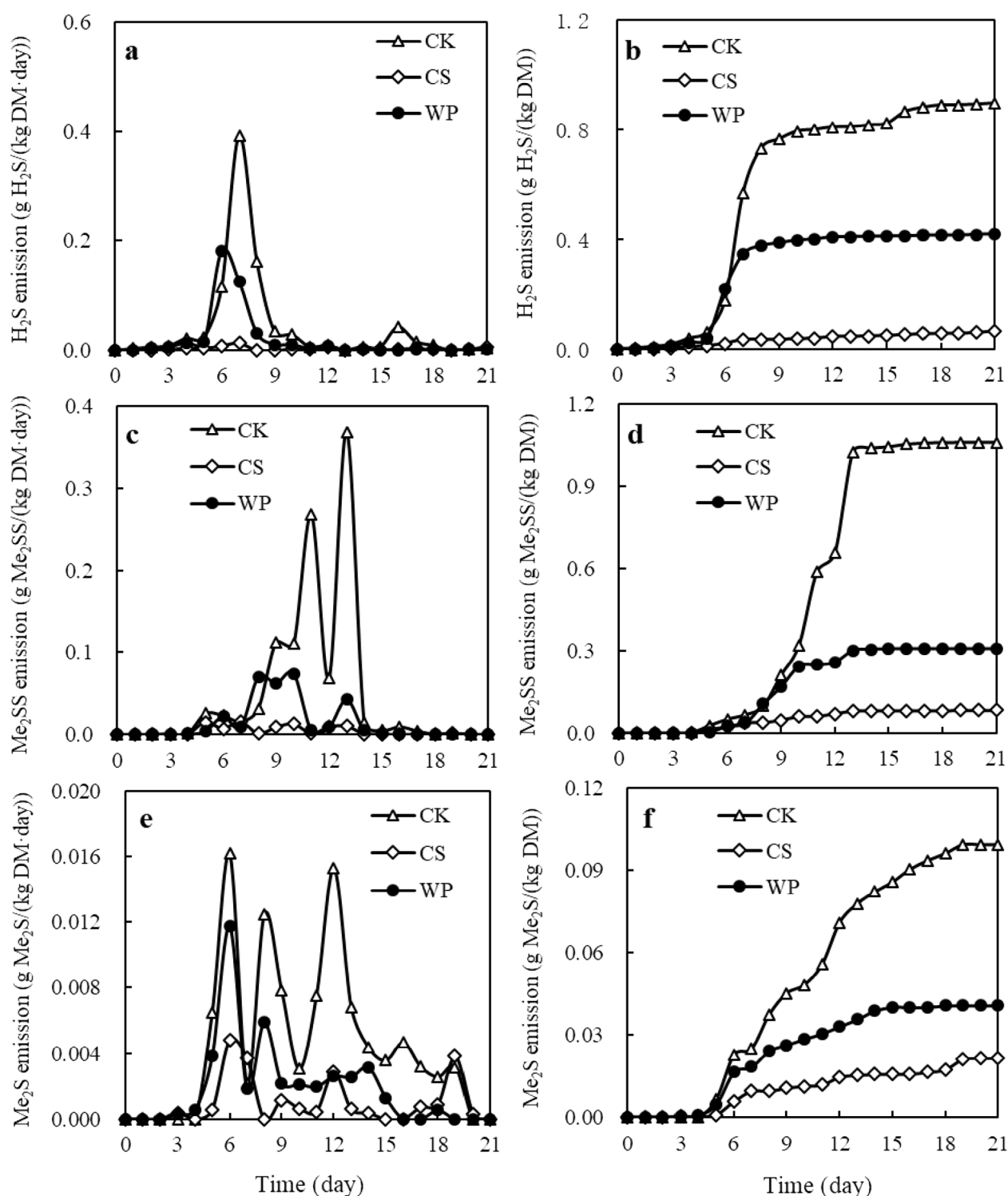


Fig. 5 – (a)  $\text{H}_2\text{S}$  emission rates, (b) cumulative emissions of  $\text{H}_2\text{S}$ , (c) dimethyl disulfide ( $\text{Me}_2\text{SS}$ ) emission rates, (d) cumulative emissions of  $\text{Me}_2\text{SS}$ , (e) dimethyl sulfide ( $\text{Me}_2\text{S}$ ) emission rates, and (f) cumulative emissions of  $\text{Me}_2\text{S}$  during the biodrying processes. Standard deviations of mean values ( $n = 3$ ) of  $\text{H}_2\text{S}$  emission rates (a) and cumulative emission of  $\text{H}_2\text{S}$  (b) in the range of 0–0.04 g  $\text{H}_2\text{S}$ -S/(kg DM·day) and 0.01–0.12 g  $\text{H}_2\text{S}$ -S/(kg DM). Standard deviations of mean values ( $n = 3$ ) of  $\text{Me}_2\text{SS}$  emission rates (c) and cumulative emission of  $\text{Me}_2\text{SS}$  (d) in the range of 0–0.03 g  $\text{Me}_2\text{SS}$ -S/(kg DM·day) and 0.01–0.09 g  $\text{Me}_2\text{SS}$ -S/(kg DM). Standard deviations of mean values ( $n = 3$ ) of  $\text{Me}_2\text{S}$  emission rates (e) and cumulative emission of  $\text{Me}_2\text{S}$  (f) in the range of 0–0.004 g  $\text{Me}_2\text{S}$ -S/(kg DM·day) and 0.001–0.016 g  $\text{Me}_2\text{S}$ -S/(kg DM).

**Table 3 – Carbon, nitrogen, and sulfur balances.**

Treatment	Dry matter loss (%)	Total carbon (%)			Total nitrogen (%)				Total sulfur (%)		
		Initial	Final	Loss <sup>a</sup>	Initial	Final	Loss <sup>b</sup>	NH <sub>3</sub> -N <sup>d</sup>	Initial	Final	Loss <sup>c</sup>
CK	47.29	36.29	28.10	48.25	1.70	2.30	26.68	19.50	0.47	0.51	42.37
CS	40.80	36.59	29.77	42.40	1.62	2.37	10.51	8.25	0.43	0.58	14.91
WP	32.73	40.93	37.88	30.49	1.60	1.98	15.23	7.22	0.43	0.50	20.95

<sup>a</sup> Total C loss(%) =  $\frac{(\text{TC of raw materials}) - (\text{TC of final product})}{\text{TC of raw materials}}$  (%).

<sup>b</sup> Total N loss.

<sup>c</sup> Total S loss are calculated analogously to total C loss.

<sup>d</sup> Percentage of the initial total nitrogen content of the raw materials on a dry weight basis.

**Table 4 – Percentages of the initial sulfur content lost as specific sulfur-containing odorous compounds.**

Treatment	Emission loss (% of initial sulfur)									
	Total	COS	H <sub>2</sub> S	CS <sub>2</sub>	Me <sub>2</sub> S	Me <sub>2</sub> SS	MeSH	EtSH	Et <sub>2</sub> S	Unknown <sup>*</sup>
CK	42.37	0.019	11.282	0.004	0.664	9.642	<0.001	0.000	0.000	20.759
CS	14.91	0.000	2.087	0.000	0.179	1.351	0.000	0.000	0.000	11.295
WP	20.95	0.000	7.122	0.001	0.367	3.767	0.000	0.000	0.000	9.691

COS: carbonyl sulfide; H<sub>2</sub>S: hydrogen sulfide; CS<sub>2</sub>: carbon disulfide; Me<sub>2</sub>S: dimethyl sulfide; Me<sub>2</sub>SS: dimethyl disulfide; MeSH: methyl mercaptan; EtSH: ethyl mercaptan; Et<sub>2</sub>S: diethyl sulfide.

<sup>\*</sup> The percentage for unknown compounds was calculated by subtracting the percentages for the eight specific compounds from the total loss of sulfur.

Larger amounts of sulfur-containing odorous chemicals were emitted during the CK treatment than during the CS and WP treatments. This may have been because sulfur-transforming bacteria benefit from anaerobic zones that form when the moisture content in a compost mixture is high. The sulfur compound concentration in the compost material decreased as the moisture content decreased. Adding a bulking agent appears to be an effective way of controlling the production and emission of sulfur-containing odorous compounds. Adding cornstalks or wood peat to the kitchen waste strongly decreased the H<sub>2</sub>S, Me<sub>2</sub>S, and Me<sub>2</sub>SS concentrations. Blazy et al. (2014) found that more MeSH than other odorous compounds was produced when pig slaughterhouse sludge was composted. No MeSH (which has a stronger odor than Me<sub>2</sub>S and Me<sub>2</sub>SS) was produced during the CS and WP treatments.

### 3. Conclusions

Adding a bulking agent to the kitchen waste increased the water-removal capacity and biodrying index, and adding cornstalks improved these parameters more than adding wood peat. The water-removal rates for CK, CS, and WP treatments were 0.35, 0.56, and 0.43 kg/kg, respectively. H<sub>2</sub>S and Me<sub>2</sub>SS were the predominant sulfur compounds (>95%) that were emitted during the 21-day biodrying. Adding cornstalks decreased the amount of NH<sub>3</sub> produced by 55.8% and reduced the total loss of sulfur by 64.8%. Adding wood peat decreased NH<sub>3</sub> emissions by 71.7% and reduced the total loss of sulfur by 50.6%.

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