

## Performance of co-composting waste activated sludge and aged refuse

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### ABSTRACT

This study was performed to investigate the effects of aged refuse (AR) as an amendment on waste activated sludge (WAS) composting dynamics. Four dosages of AR (5%, 10%, 15% and 20%, on WAS dry weight basis) were amended to WAS for composting during a 36 d period. Cornstalks were added at 15% (of total wet weight of WAS) to improve the co-composting process. Results show that appropriate AR proportion could rapidly initialize the co-composting process, enhance organic content for biodegradation, and increase the humification degree during composting. Moreover, AR significantly decreased total nitrogen losses and plant toxicity. The maturity parameters indicate that compost with AR became more matured and humified within 36 d of composting, with the maturity parameters being within the permissible limits of organic farming in contrast to the control without AR.

*Keywords:* Waste activated sludge; Composting; Aged refuse; Nitrogen losses; Humic substances

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### 1. Introduction

With the rapid development of urbanization in China, a large number of wastewater treatment plants (WWTPs) have been established, resulting in the production of large quantities of waste activated sludge (WAS). The annual yield of WAS in China was estimated to be 30 million tons, accounting for one-fourth the production of total organic waste in China [1]. WAS contains abundant organic matter and nutrients such as nitrogen and phosphorus. Moreover, WAS contains organic contaminants (such as dioxin compounds, polycyclic aromatic hydrocarbons), heavy metals, pathogens and antibiotics (such as tetracyclines, sulfonamides, fluoroquinolones and macrolides), which could cause potential risk to the environment and ecological system [2]. Therefore, WAS should be treated effectively and properly, which may otherwise cause the second environmental pollution and the waste of resources [2].

The treatment and disposal cost of WAS is high, accounting for up to 20% of total operating cost of a

WWTP [3]. Composting is an extensively employed method for WAS treatment with cost-effectiveness and social acceptability [4]. Composting has been defined as a controlled microbial decomposition process with the formation of stabilized organic materials that may be used as soil conditioners and/or organic fertilizer [5]. Microbes in compost include bacteria, fungi, protozoa and invertebrates. The effectiveness of the composting process is influenced by factors such as temperature, oxygen supply, moisture content, pH, C:N ratio, bulking agents and degree of compaction [3–5].

Nevertheless, conventional composting can lead to severe nitrogen loss, greenhouse gas emissions and enrichment of heavy metals [6]. Moreover, the number of beneficial microbes is low during the early stage of composting. Therefore, conventional composting is encountered with some limitations such as long duration, odour and low fertilizer efficiency [7,8]. Some of these issues could be solved to a certain extent through microbial inoculation in composting materials [9]. However, the screening and cultivation of specific microorganisms are time-consuming, laborious and

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high-cost. Moreover, the inoculation effect can be low when the inoculated microorganisms are not suitable to the high temperature composting conditions [9].

Currently, sanitary landfill is a main disposal way of municipal solid waste (MSW) in China. The rapid development of urbanization in China results in the increase of land price and difficulty in site selection of the landfill. Refuse in landfills and dumping sites becomes aged and stabilized after 8–10 years of placement, and the resultant partly or fully stabilized refuse is referred to as aged refuse (AR) [10]. The degradable substances in AR are nearly completely degraded, the surface settlement of landfill site is generally less than 1 cm/a, little or no leachate and gas was generated, and the concentration of chemical oxygen demand in leachate is low [10]. The excavation of AR can reuse landfill space and recover recyclable materials. Nevertheless, the excavated AR should be properly treated to prevent secondary pollution.

AR contains high concentrations of enzymes including oxidoreductase and hydrolase [11]. These enzymes are highly active and adaptable, and can rapidly degrade pollutants through multiple enzymatic reactions. AR has high specific surface areas and porosity, as well as excellent physical–chemical properties and hydraulic properties [12]. Additionally, a wide spectrum and large quantity of microbes can be enriched in AR due to the special formation conditions and heterogeneous architectures [11]. These microbial communities have been proved to have a strong decomposition capability for both biodegradable and recalcitrant organic pollutants [11]. All of these special advantages provide favorable conditions for the utilization of AR.

The aim of this work is, therefore, to investigate the performance of co-composting AR and WAS at different proportions. The effect of different dosages of AR on the digestion of sludge was investigated.

## 2. Material and methods

### 2.1. Composting materials

Mechanically dewatered WAS used in this work was obtained from a WWTP (Nanchang, China). WAS was stored at 4°C prior to use. The AR for this work was excavated from a 10-year-old enclosed chamber at the Maiyuan MSW landfill in Nanchang city. The larger substances, such as plastics, metals, rubbers, stones, glass, etc., were manually separated and removed by filtering through a 20 mm mesh. In this study, cornstalks were used as the bulking agent to adjust the moisture and free air space of composting materials. Cornstalks were collected from a farmland nearby and cut to 2–3 cm after being air dried. Key physicochemical characteristics of these raw materials are listed in Table 1.

### 2.2. Experimental system and protocol

In this study, AR was used as the microbial inoculant for WAS composting. The investigation was carried out using five replicate stainless steel reactors with a working volume of 3.5 L each. The reactors had 5 cm thick insulation layer of polyurethane foam. The reactors were mounted on a rotating shaft, and they could spin around its horizontal

axis to ensure the good homogenizing of the composting mix. The reactors were equipped with an aeration system that supplied 1.6 L of fresh air per minute. Each reactor had a digital thermometer in the central of the composting pile to record temperature. Reactor-1 to reactor-6 were fed with 500 mL of WAS and different amounts of AR at 0, 5%, 10%, 15%, and 20% (on WAS dry weight basis). Additionally, 15% cornstalks (proportions of WAS, wet weight) were used as the bulking agent and mixed with WAS/AR mixture. This proportion (15%) has been reported to be the optimum additive amount for adjusting moisture content and C/N ratio of composting materials [13].

The composting material was mixed by rotating for 30 min once a day. Average samples (from the top, middle and bottom of the composting piles) were taken regularly, immediately after mixing. They were then subdivided into two portions: one portion was stored at 4°C; the second was dried, grounded to pass through a 1 mm sieve, and subsequently sealed in plastic containers.

### 2.3. Analytical methods

The pH was determined by using a pH meter (PHS-3C, Shanghai Precision & Scientific Instrument Co. Ltd., China) after mechanically mixing the samples with deionized water (1:10 w/v). Moisture content was measured by drying the samples at 105°C to constant weight. Total organic carbon (TOC) and total nitrogen (TN) were determined by a multi N/C 2100 TOC/TN analyzer (Analytik Jena AG, Germany). Nitrogen as  $\text{NH}_4^+$  and  $\text{NO}_3^-$  were extracted using 2 M KCl solution and analyzed using an air-segmented flow analyzer (Technicon Autoanalyzer; Bran & Luebbe, Hamburg, Germany). A portable gas analyzer (Geotech GA2000, Warwickshire, UK) was used for measuring biogas composition. The  $\text{NH}_3$  trapped in 2% boric acid was titrated using 0.1 N  $\text{H}_2\text{SO}_4$ . The germination index (GI) was used to assess the compost phytotoxicity according to the study by Zhang and Sun [14].

### 2.4. Humic substances extraction

The extraction of humic substances was conducted using the combined methods of Zhou et al. [15] and Kulikowska [17]. In brief, before humic substances extraction, compost samples were washed three times with distilled water to remove water-soluble non-humic substances (sugars, proteins, etc.). Then the samples were defatted several times with a 2:1 (v/v) chloroform–methanol mixture until a colorless supernatant was obtained. After solvent evaporation, the defatted samples were extracted with a 0.1 mol/L  $\text{NaP}_2\text{O}_7$ –NaOH solution after shaking at 200 rpm for 24 h at room temperature using a solid/extractant ratio of 1:10 (w/v, dry weight basis). The supernatant was centrifuged at  $15,000 \times g$  for 30 min, and the extraction/centrifugation procedure was repeated two times and the extracts were pooled together. The extractant was adjusted to pH 7.0 with 0.5 M HCl and the TOC of humic substances was analyzed by a multi N/C 2100 TOC/TN analyzer (Analytik Jena AG, Germany). The humic substances were further fractionated into the humic acid (HA) and fulvic acid (FA) parts by acidification and precipitation as described by Zhou et al. [15].

### 2.5. Statistical analysis

The mean value and standard deviation of three replicates of each treatment were reported on a dry weight basis. The data were analyzed using one-way analysis of variance. ANOVA was carried out for each treatment to determine significant differences at level  $p < 0.05$ .

## 3. Results and discussion

### 3.1. Effect of AR addition on the variation in humic substances

During composting, the transformation of organic matter consists of two processes: degradation/mineralization and humification [16]. Compost quality is defined by its maturity and stability, which is correlated with the transformation of organic matter during composting. Humic substances can efficiently stimulate plant growth and improve soil fertility. Therefore, the variation in humic substances can be a good indicator of composting progress [15,17].

The influence of AR dosage on the variation in humic substances was first investigated and the results are plotted in Fig. 1a. As shown, the curves can be divided into two phases, namely an initial decrease followed by an increase of humic substance contents. The contents of humic substances declined during the initial stage of composting across various treatments. The initial decrease of humic substance contents was attributed to the dramatic reduction of FA at this phase in all treatments (Fig. 1c). Humic substances are mainly comprised of HA and FA fractions. It is known that the FA fraction is much more easily biodegraded than the HA fraction [18]. Thus, the contents of humic substances decreased during the initial composting stage due to the rapid biodegradation of FA (Figs. 1a and c).

During the second stage, the humic substance contents continuously increased with time (Fig. 1a). The contents of humic substances in the final compost piles with 0, 5%, 10%, 15% and 20% AR were 82.3, 105, 126, 114 and 103 g/kg (Fig. 1a), respectively, the contents of HA were 49.4, 66.2, 78.3, 71.3 and 63.5 g/kg (Fig. 1b), respectively, and the contents of FA were 31.5, 37.5, 46.4, 41.2 and 37.8 g/kg (Fig. 1c), respectively. The final content of humic substances increased from 82.3 to 126 g/kg with the increase of AR dosage from 0 to 10% (Fig. 1a). However, further increment of AR did not enhance the production of humic substances. For instance, the maximum content of humic substances with 20% AR was 131 g/kg, which was close to that with 10% AR addition. Compared with their initial values, the contents of humic substances and HA in the final composts piles increased by 26.2%–89.8% and 119%–237%, respectively, across various treatments; whereas the contents of FA decreased by 32%–3.3%.

During composting, microbial activity and enzymatic reactions of polymerization/repolymerization caused the formation of aromatic and aliphatic compounds such as humic substances [19]. In the present study, the higher increment in the contents of humic substances and HA in the compost piles with AR addition may be caused by more degradation of organic matters (Figs. 1a and b). During composting, the microorganisms utilized organic matters including FA for their metabolism and involved in the organic matter transformation towards HA [15]. The addition of AR

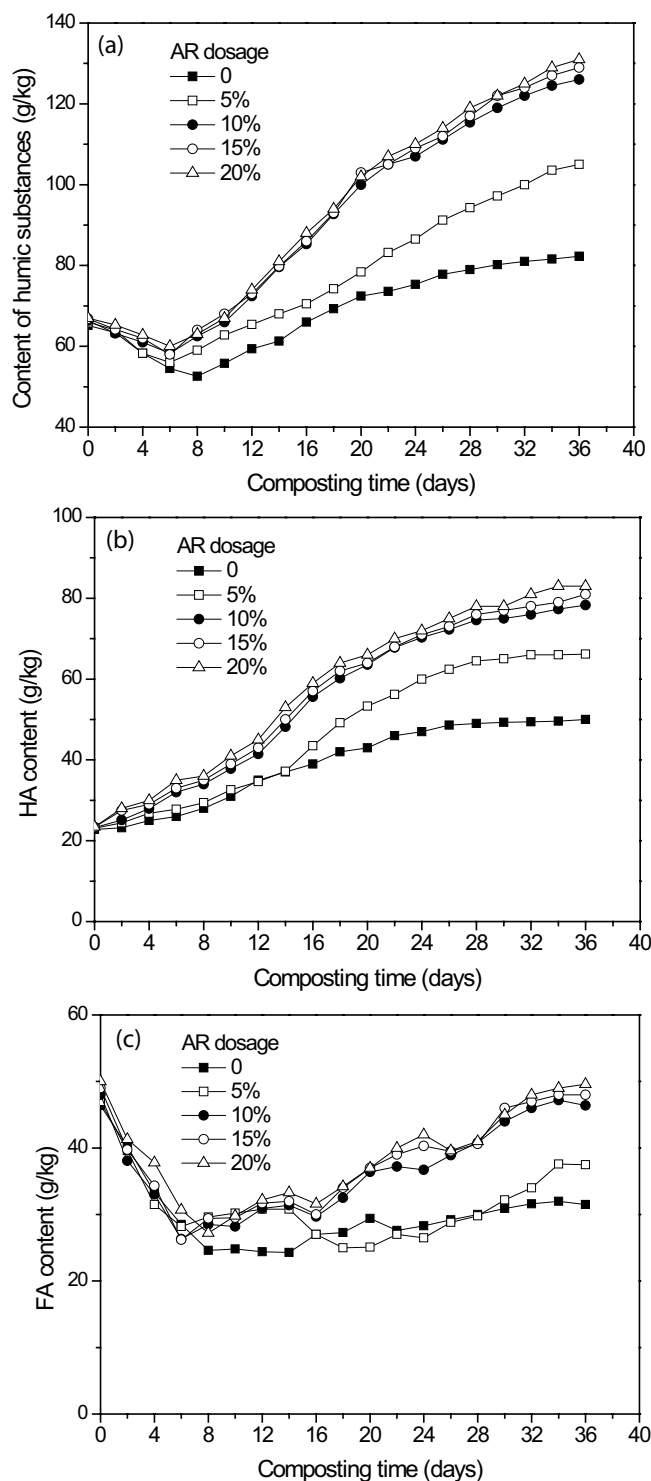


Fig. 1. Changes in the extractable humic substances (a), HA (b), and FA (c) during the composting of sludge with addition of different dosages of AR.

could provide key microorganisms and enzymes, which was beneficial for the decomposition and utilization of organic matters. Actually, the activities of protease,  $\alpha$ -glucosidase, phosphotransacetylase and acetate kinase were as high as 1.33, 4.52, 0.68 and 2.35 U/g in the AR. Moreover, the main

microbes detected in the AR were affiliated to Proteobacteria, Bacteroidetes and Firmicutes (accounting for 66.2% of the total microbial sequences). Several bacteria affiliated to Proteobacteria and Bacteroidetes phyla were also reported to be the key microorganisms involving in sludge hydrolysis and organics degradation [20], and their introductions were also beneficial for the enhancement of sludge composting.

At the current stage, we could not exclude the possibility whether AR was degraded by microorganisms during the composting process. Nevertheless, the increase of humic substances with AR addition was mainly due to the enhanced formation of HA rather than the exogenous input by AR addition, because the TOC content of AR was remarkably lower than that of WAS (Table 1).

### 3.2. Effect of AR addition on the variation in inorganic nitrogen

During the composting process, nitrogen transformation reactions could occur simultaneously, such as ammonification, ammonia assimilation, nitrification and denitrification. The dominant reaction could change according to the substrate and environmental conditions in composting.

As shown in Fig. 2a,  $\text{NH}_4^+\text{-N}$  profiles were similar across all treatments.  $\text{NH}_4^+\text{-N}$  contents of all treatments increased rapidly at the beginning of composting. This phenomenon is attributed to the mineralization of nitrogen-containing organic compounds, indicating the activity and dominance of microbial ammonification in the initial stage of composting [21,22]. The treatment with 10% AR experienced a more active microbial ammonification within the first 6 d, and its  $\text{NH}_4^+\text{-N}$  content increased more rapidly than other treatments (Fig. 2a). After the maximum at day 6, the  $\text{NH}_4^+\text{-N}$  content decreased gradually for all treatments, mainly due to the

volatilization of  $\text{NH}_3$  and the biological conversion of  $\text{NH}_4^+\text{-N}$  to  $\text{NO}_3^-\text{-N}$  [23]. At the end of composting, the  $\text{NH}_4^+\text{-N}$  content was in the range of 0.40–0.94 g/kg for the five treatments. Compared with their initial contents (1.24–1.43 g/kg), the  $\text{NH}_4^+\text{-N}$  content was reduced by 34.3%–67.7%. Compared with the control without AR, treatments with addition of AR had lower  $\text{NH}_4^+\text{-N}$  contents at the end of composting. Obviously, the addition of AR could reduce the  $\text{NH}_4^+\text{-N}$  content of sludge/cornstalk/AR compost, since AR had lower  $\text{NH}_4^+\text{-N}$  concentration than sludge (Table 1). Another reasonable explanation was that the addition of AR stimulated the microbial conversion of  $\text{NH}_4^+\text{-N}$  to bio-nitrogen and nitrate retained in the compost.

In this work, nitrification was detected by the formation of  $\text{NO}_3^-\text{-N}$ . Fig. 2b shows the change of  $\text{NO}_3^-\text{-N}$  contents. At the beginning of composting, the nitrate content was low and stable in all treatments (Fig. 2b). This indicates that little nitrification occurred in the initial phase, due to the inhibition of activity and growth of nitrifying bacteria by excessive amounts of  $\text{NH}_4^+\text{-N}$  in the compost [24]. After the lag period, as the mineralization of nitrogenous organic matter started, the nitrate contents gradually increased in all treatments until the end of composting (Fig. 2b). When compared with the control without AR, the AR amended treatments had higher nitrate contents at the end of composting (Fig. 2b), possibly due to their more desirable conditions for nitrification during composting. Nevertheless, when the AR dosage was increased from 10% to 20%, no significant increment was found in the nitrate contents.

Fig. 2c shows the changes in the TN contents of composting material with time. As shown, the TN contents first declined and then gradually increased during the composting period. The decrease of TN contents is attributed

Table 1

Key physicochemical characteristics of raw composting materials (average value  $\pm$  standard deviation of three triplicates, on the dry weight basis)

Parameters	Sludge	Cornstalk	Aged refuse
Moisture content (%)	81.6 $\pm$ 1.8	8.1 $\pm$ 0.5	30.6 $\pm$ 1.2
Total organic matter (g/kg)	853 $\pm$ 9	412 $\pm$ 11	73 $\pm$ 4
Total organic carbon (g/kg)	275 $\pm$ 12	246 $\pm$ 13	38 $\pm$ 3
Total nitrogen (g/kg)	34.3 $\pm$ 1.6	6.8 $\pm$ 0.6	5.3 $\pm$ 1.1
Ammonium nitrogen (g/kg)	1.4 $\pm$ 0.10	0.08 $\pm$ 0.01	0.6 $\pm$ 0.1
Nitrate nitrogen (g/kg)	0.31 $\pm$ 0.03	0.18 $\pm$ 0.01	0.23 $\pm$ 0.01
Electrical conductivity (mS/cm)	0.3 $\pm$ 0.1	2.4 $\pm$ 0.5	6.4 $\pm$ 0.5
pH	7.3 $\pm$ 0.2	7.1 $\pm$ 0.1	7.6 $\pm$ 0.3
Specific surface area (m <sup>2</sup> /g)	–	–	4.33 $\pm$ 0.16
Porosity (%)	–	–	46 $\pm$ 1.1
Total bacteria (cfu/g)	–	–	(1.2 $\pm$ 0.2) $\times$ 10 <sup>7</sup>
Humic acid (g/kg)	–	–	22.5 $\pm$ 1.6
Fulvic acid (g/kg)	–	–	5.3 $\pm$ 0.5
Cd (mg/kg)	0.62 $\pm$ 0.05	–	76 $\pm$ 5
Cu (mg/kg)	325 $\pm$ 14	–	240 $\pm$ 13
Zn (mg/kg)	1,120 $\pm$ 32	–	226 $\pm$ 11
Cr (mg/kg)	430 $\pm$ 14	–	45 $\pm$ 3
Pb (mg/kg)	86 $\pm$ 5	–	413 $\pm$ 21
Ni (mg/kg)	522 $\pm$ 9	–	226 $\pm$ 15

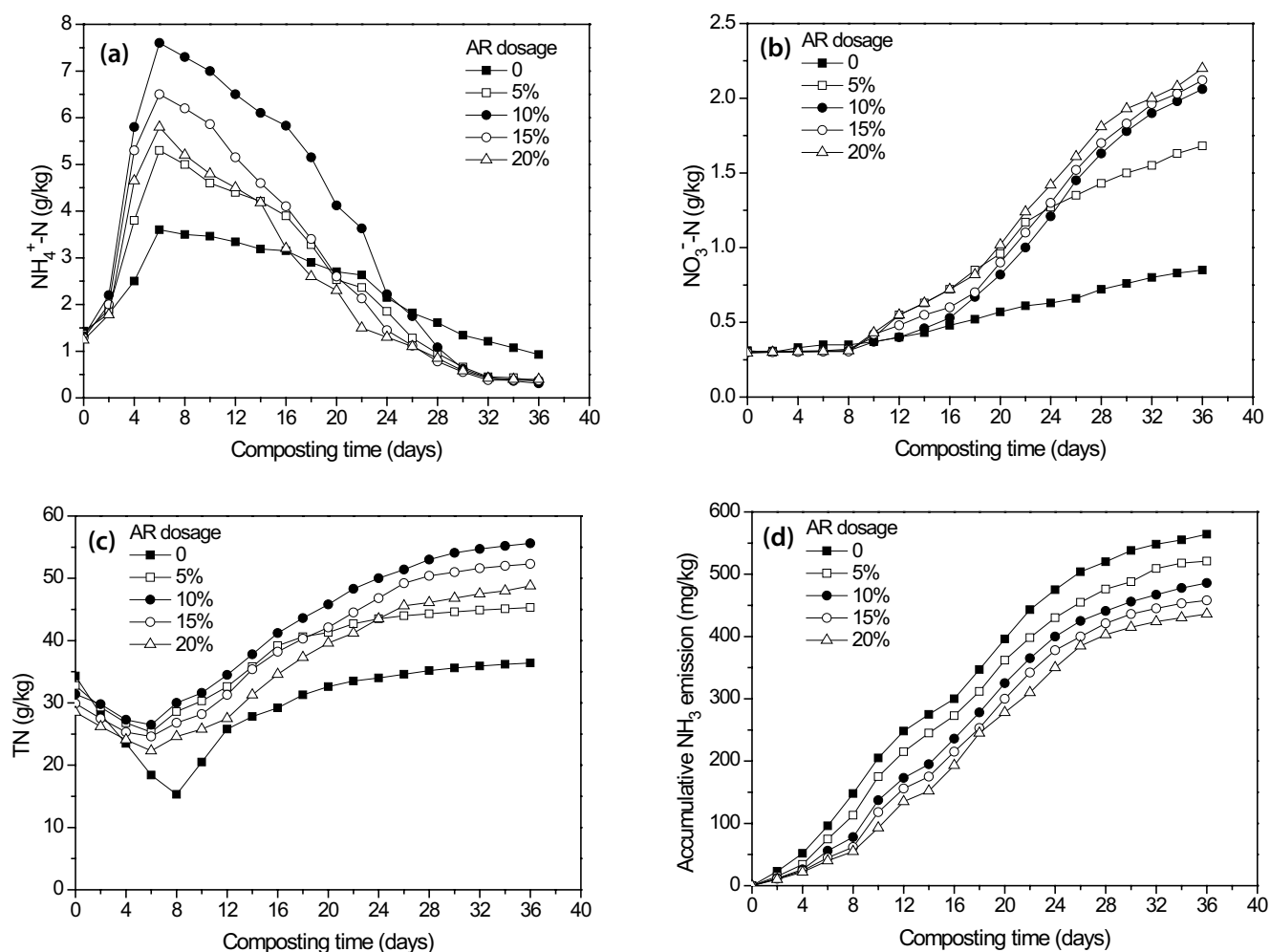


Fig. 2.  $\text{NH}_4^+\text{-N}$  (a),  $\text{NO}_3^-\text{-N}$  (b), TN (c) contents and accumulative  $\text{NH}_3$  emission (d) in different treatments during the composting of sludge with addition of different dosages of AR.

to ammonia volatilization and microbial catabolism of nitrogen. The subsequent increment of TN contents was caused by organic degradation during composting. It is known that the TN content increased during composting due to the more significant reduction of composting material than TN loss [21]. It is observed that the content of TN in the control was lower than that in all AR amended treatments (Fig. 2c), which could be a low decomposition of organic matters or a higher loss of ammonia [25]. In this study, the TN content in the final compost was increased by 38.1%–77.1% for the AR-amended treatments when compared with their initial contents. However, less increment was observed for the control (only 6.1%). This result could be attributed to the higher microbial activity in composting materials of the AR amended treatments, resulting in higher biodegradation of organic matter and thus more reduction in the total mass [26]. As a result, the C/N ratio decreased for all treatments (from 22.4–28.5 to 13.6–18.3). The C/N ratio was lower than 25 for all AR-amended treatments at the end of composting, which is commonly recommended for mature compost [27].

The evolution of accumulative  $\text{NH}_3$  emission is shown in Fig. 2d. The  $\text{NH}_3$  emission rate in treatments with AR

addition, especially the 20% AR-amended treatment was significantly lower than the control without AR. The AR used in this work has high specific surface areas and porosity as well as abundant microbial communities (Table 1). Therefore, the addition of AR in composting could reduce ammonia emission by increasing the microbial ammonia assimilation and absorbing precursors such as ammonium nitrogen, urea and uric acid from composting mixtures.

### 3.3. Effect of AR addition on $\text{CO}_2$ emissions

The  $\text{CO}_2$  emission was directly correlated with the overall microbial activity and humification. The evolutions of  $\text{CO}_2$  emissions in all treatments are compared in Fig. 3. After composting began,  $\text{CO}_2$  emissions from all AR (5%, 10%, 15%, and 20%) amended treatments increased rapidly and the peaked values 46.3, 62.1, 68.6 and 72.4 g  $\text{CO}_2\text{-C}$  were observed on day 6, 4, 4 and 4, respectively (Fig. 3) and then gradually decreased until the maturation phase of composting. In contrast, significantly lower  $\text{CO}_2$  emission occurred from the control during the composting. This indicates that AR addition could provide favorable condition for biological

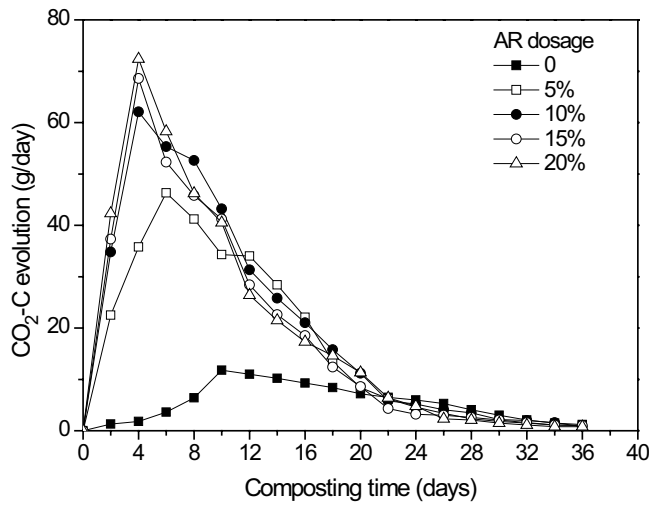


Fig. 3. Evolutions of daily  $\text{CO}_2$  emissions in different treatments during the composting of sludge with addition of different dosages of AR.

activities and thus rapid mineralization of organic waste occurred. Namely, AR addition caused both higher organics biodegradation and more rapid organics mineralization (corresponding to  $\text{CO}_2$  emission). AR addition may bring a large amount of functional microbes and enzymes, enhancing the decomposition of sludge organics.  $\text{CO}_2$  emission is characteristics of a gradual stabilization of the feedstock, and this is frequently used as a maturity index for reflecting the overall microbial activities [28,29]. When compared with the control, addition of AR increased cumulative  $\text{CO}_2$  emission by approximate 50%–60%, which might be obvious from that AR addition caused a relatively long duration of thermophilic phase and enhanced the decomposition of sludge.

### 3.4. Germination index

The seed germination test was generally employed to evaluate the toxicity and maturity of compost Zhang and Sun [14]. Fig. 4 shows the evolution of GI during composting. The GI of the control and all AR amended treatments declined in the first 4 and 2 d, respectively. This decrease

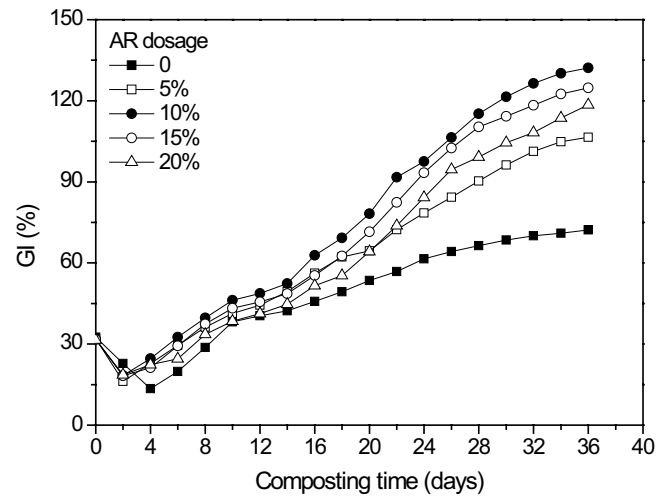


Fig. 4. Evolution of GI in different treatments during the composting of sludge with addition of different dosages of AR.

could be ascribed to the production of low molecular weight short chain volatile fatty acids and ammonia [24]. After the initial decrease, the GI of all treatments increased gradually until the end of composting (Fig. 4). The increase of GI was caused by the decomposition of toxic substances in the composting piles. The results show that the GI values were higher in 10% AR amended treatment than those in the other treatments containing 5%, 15%, and 20% AR or without AR. The final GI values in the control, 5%, 10%, 15%, and 20%, AR amended treatments were 72.2%, 106.5%, 132.2%, 124.8%, and 118.5%, respectively. According to Tiquia and Hodgkiss [30], the GI higher than 80% indicates phytotoxic-free and mature compost. In this work, the GI values exceeded 80% at the end of experiments for all AR amended treatments. The significantly increased GI by AR addition suggests that the degradation of organics, especially toxic substances, could be enhanced by AR addition.

### 3.5. Quality of the end products

The physical properties and nutrient contents in the composts are important indicators for evaluating the quality

Table 2

Selected maturity properties of composts obtained from all treatments (dry weight basis) (mean  $\pm$  standard deviation)

Parameters	AR dosage					TMECC standard <sup>a</sup>
	0	5%	10%	15%	20%	
pH	6.8 $\pm$ 0.1a	6.6 $\pm$ 0.1a	6.7 $\pm$ 0.1a	6.6 $\pm$ 0.1a	6.6 $\pm$ 0.1a	5.5–8.5
Electrical conductivity (mS/cm)	1.43 $\pm$ 0.05a	0.95 $\pm$ 0.04b	0.83 $\pm$ 0.03b	0.86 $\pm$ 0.05b	0.9 $\pm$ 0.02b	$\leq$ 4
$\text{CO}_2$ evolution rate (g C/(kg VS) day)	7.34 $\pm$ 0.75a	1.52 $\pm$ 0.07b	1.36 $\pm$ 0.05b	1.33 $\pm$ 0.03b	1.38 $\pm$ 0.04b	2–4
Ammonium (mg/kg)	930 $\pm$ 4a	352 $\pm$ 3.6c	316 $\pm$ 2.2d	379 $\pm$ 2.7c	402 $\pm$ 3.1b	75–500
Total organic matter (g/kg)	721 $\pm$ 11a	563 $\pm$ 9b	483 $\pm$ 8c	465 $\pm$ 13c	451 $\pm$ 6c	$\geq$ 400
C:N ratio	18.3 $\pm$ 0.2a	16.8 $\pm$ 0.1b	13.6 $\pm$ 0.1c	13.9 $\pm$ 0.3c	14.1 $\pm$ 0.2c	$\leq$ 25
Seed germination index (%)	72.2 $\pm$ 1.4a	106.5 $\pm$ 2.1b	132.2 $\pm$ 1.7cd	124.8 $\pm$ 3.2c	118.5 $\pm$ 2.5c	80–90

<sup>a</sup>TMECC: test methods for the examination of composts and composting.

Values within a row followed by different lowercase letters are significantly different at  $p < 0.05$ .

of sludge compost when being used as fertilizers or soil amendments. Table 2 summarizes the maturity properties for all treatments. As shown, the range of various parameters in composts at the end of composting was within the permissible limits for compost [27]. The nutrient content in all AR added treatments were significantly higher ( $p < 0.05$ ) than in the control without amended treatments (Table 2). In the control treatment compost, some nutrient contents were within the permissible limit, but the seed GI and CO<sub>2</sub> respiration indicate that this compost was not properly stabilized and mature for organic farming (Table 2). The above result shows that the combined addition of AR in the WAS composting process not only reduced the composting time but also enhanced the organic matter mineralization and the quality and stability of the end product. Nevertheless, due to the differences in the compositions of WAS and AR, the composts are different in properties and therefore have different effects when applied to soils.

#### 4. Conclusions

This study reports a low-cost alternative strategy, that is, adding appropriate AR into WAS digestion systems to significantly improved the processes of sludge composting. Experimental results show that pertinent addition of AR enhanced the humification with significant reduction of total nitrogen loss, promoted the degradation of toxic substances, and improved the maturity properties and agronomic value of the end products. Overall, the addition of appropriate amounts of AR for sludge composting demonstrates to be a beneficial practice for the management of WAS.

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