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Simultaneous metal leaching and sludge digestion by thermophilic microorganisms: Effect of solids content

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ABSTRACT

High concentrations of heavy metal in livestock manures limit land application of their sludges. A practical and economical method of sludge treatment is important for converting the livestock sludge into soil conditioners or fertilizers. In this study, the effect of solid contents on the simultaneous aerobic digestion and metal leaching at thermophilic condition were investigated in a batch reactor. Different solid contents in the range of 0.5–4% (dry-w/v) were studied. The results showed that an increase of solid content decreased the pH reducing rate. It was the result of increase in buffering capacity and possible microbial inhibition at a higher solid content. Similar results were also found in the variations of ORP and sulfate concentrations during this process. In most cases, this biological process is able to solubilize 82–99% of heavy metals from the livestock sludge. It was found that the efficiency and rate of metal solubilization decreased with increasing solid contents. In addition, 54–80% of organic matter in the sludge was degraded after 28 days of reaction. A low sludge digestion efficiency was found at a high solid content. Moreover, the dewaterability of sludge was improved and the fertility (N, P and K) of sludge did not change significantly after this bioprocess.

1. Introduction

Due to limited land in Taiwan, the management of swine farming tends toward a high intensity confinement system instead of a pasture-based system. In general, the wastewater produced from swine farms was one of the main sources polluting rivers in Taiwan. To protect the waterways and the sustainable growth of the swine production industry in Taiwan, the government imposed effluent standards for the industry. Therefore, the management of wasted sludge produced from the wastewater treatment facilities becomes a pressing issue for the swine farms. Rather than the landfills and incineration for sludge treatment, the swine sludge containing abundant nutrients and hydrocarbons is favourably applied to agricultural lands as soil conditioners or fertilizers. This way of sludge disposal achieve dual benefits of nutrient recycling and waste minimization of swine farms. Although such application may be beneficial to soil, the negative impacts such as groundwater pollution, pollutant accumulation in soil, etc., should be also considered [1]. Elevated heavy metals concentration in sludge limits the utilization of swine sludge in agriculture and land application [2,3]. There is a need to find an economically feasible and environmentally friendly process to remove heavy metals from swine sludge.

Although some physical or chemical techniques have been implemented for treating the sludge containing heavy metals such as acid/solvent extraction, acid/alkaline thermal hydrolysis and Fenton's peroxidation, the shortcomings of the requirement of large amount of chemicals, high operating cost, the operational difficulties and the secondary pollution problems restrict their applications [4,5]. Because of simplicity, low operating and capital costs, and environmentally friendly [6,7], the microbial leaching is considered as an efficient and economical technology to remove heavy metals from sludge, soil or sediment [8–11]. Tyagi et al. [12] showed that the microbial leaching is 80% cheaper in terms of chemical consumption compared to the traditional chemical methods employed for metal leaching from the sludge and recovery of metals from the leachate. Moreover, Sreekrishnan and Tyagi [13] further reported that the microbial leaching process is less costly as compared to the conventional aerobic digestion and metal leaching by acid addition or iron-oxidizing process, especially at small-scale operation and at high solids content. In the microbial leaching process, the removal of heavy metals from sludge is mainly achieved by the oxidation and acidification reactions caused by sulfur-oxidizing bacteria. The microorganisms mainly involved in the microbial leaching process belong to the genus *Acidithiobacilus* or *Thiobacillus*, specially including *At. thiooxidans*, *At. ferrooxidans* and *T. thioparus* [8]. Generally, acclimated indigenous microorganisms are used as

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the inoculums in the microbial leaching process to attain the high efficiency of metal solubilization [14]. However, when the acclimated indigenous microorganisms are inoculated in the microbial leaching process, the degradation of organic matter by indigenous heterotrophic microorganisms in the sludge also occurs, simultaneously coupled with the metal leaching reaction. Therefore, a process called simultaneous sludge digestion and metal leaching has been developed for sludge treatment [15].

It has been known that the sludge solid contents in the microbial leaching process play a significant role in determining the reactor capacity. In general, a low solid content increases the rate of microbial leaching; however, a large volume of reactor is required. Contrarily, a high solid content increases the treatment capacity, which results in a slow rate of microbial leaching and a long residence time. Kim et al. [16] showed that the rate and efficiency of metal solubilization decreased as an increase in the solid content in a microbial leaching system. Liu et al. [17] reported that the oxidation activity of *At. ferrooxidans* was inversely affected by the solid contents in the microbial leaching process because of collision and friction among solid particles. In addition, the microbial leaching process mostly performed under mesophilic conditions has shown slow metal leaching rates. However, due to higher metal tolerance capacity and metabolic characteristics at high temperature, the rates of metal leaching under thermophilic conditions are considerably enhanced [18–20]. Meanwhile, literature in simultaneous metal leaching and sludge digestion process at the thermophilic conditions is very limited. The purpose of this study was to investigate the effects of the solid contents on the performance of thermophilic simultaneous metal leaching and aerobic digestion of livestock waste sludge. The dewaterability and fertility (N, P and K) of treated sludge were also evaluated in this study.

2. Materials and methods

2.1. Sludge sampling

The sludge was obtained from an anaerobic treatment unit of the wastewater treatment plant in a local swine farm of northern Taiwan. The sludge was then screened through a 20-mesh (0.84 mm) sieve, well mixed and stored at 4 °C before the study. The swine sludge was analyzed for pH [21], total solids (TS) volatile solids (VS), suspended solids (SS), volatile suspended solids (VSS) [22], nutrient (N, P) contents and heavy metal contents. For metal content analysis, the sludge sample was digested with HNO_3–HF–HCl (5:4:1, v/v) mixture in the microwave digestion system (Model MARS Xpress, CEM), according to USEPA3052 method [23]. The total nitrogen content of the sludge was measured using a Herneus CHNOS Rapid elemental analyzer and the total phosphorus content was determined according to Method 424 C&D in Standard Methods [22]. The basic characteristics of the swine sludge are shown in Table 1.

2.2. Acclimation of sulfur-oxidizing bacteria

For acclimation, 15 g of sterilized elemental sulfur was mixed with 3 l of the swine sludge (1%, dry-w/v) in a batch reactor with an agitation speed of 200 rpm and the temperature of 55 °C. The acclimation activity of sulfur-oxidizing bacteria was determined based on sludge pH. The acclimation procedure was matured when sludge pH dropped to about 2.0. Then, a 300 ml of the acidified sludge sample was transferred to another reactor with 3 l of fresh sludge and 15 g of elemental sulfur, and the acclimation procedure was repeated at least three times. The acclimated sludge was then used as an inoculum for the simultaneous metal leaching and sludge digestion experiment.

Table 1
The characteristics of sludge used in this study.

Property	Value[a]
pH	7.3 ± 0.1
TS (%, w/w)	6.36 ± 0.12
VS (%, w/w)	3.08 ± 0.12
SS ($mg\,l^{-1}$)	55420 ± 960
VSS ($mg\,l^{-1}$)	26410 ± 530
Cu ($mg\,kg^{-1}$)	1105 ± 74
Zn ($mg\,kg^{-1}$)	3310 ± 90
Mn ($mg\,kg^{-1}$)	1824 ± 56
Ni ($mg\,kg^{-1}$)	84 ± 7
K ($mg\,kg^{-1}$)	7271 ± 345
Total-N ($mg\,kg^{-1}$)	33190 ± 940
Total-P ($mg\,kg^{-1}$)	2140 ± 60

[a] Mean ± standard deviation ($n = 10$).

2.3. Simultaneous metal leaching and aerobic digestion experiments

The experiment of simultaneous metal leaching and aerobic digestion was performed in a completely mixed batch reactor containing, 1.5 l of inoculants, 50 g of elemental sulfur, and 10 l of sludge with different solid contents (0.5–4%, dry-w/v). The batch bioreactor was maintained at 55 °C with an agitation speed of 200 rpm. The sludge in the reactor was aerated with an airflow rate of 0.3 vvm (volume of air (volume of sludge)$^{-1}$ min^{-1}). A control test (2% solid content) without inoculation and elemental sulfur addition was also carried out under the same conditions. The pH and oxidation–reduction potential (ORP) of sludge were measured continuously by an on-line pH/ORP meter (Suntex, model PC-310). During the experiments, sludge samples were periodically withdrawn for SS and VSS analyses [22]. Meanwhile, the sludge sample was filtered through a 0.45 μm filter, and the filtrate was used for analyzing sulfate concentration [22] and heavy metals. The concentrations of heavy metals were determined by a flame/graphite atomic absorption spectrophotometer (Shimadzu AA-6200). At the end of the experiments, the sludge was directly taken out for the analysis of dewaterability index (specific resistance to filtration, SRF) [24] without any neutralization and conditioning. The sludge retaining on the filter papers in SRF analysis was air dried at room temperature. The sludge was scraped and analyzed for total nitrogen, total phosphorus and potassium.

In order to confirm the degradation of solids caused by acidification, 3 l of sludge (2% solid content) was abiotically acidified by a daily stepwise addition of sulfuric acid followed a similar biotic reactor pH profile in a stirred tank reactor. This experiment of sludge acidification was also carried out at 55 °C. The pH after each step of acid addition was recorded and the sludge samples were withdrawn to determine the SS and VSS.

3. Results and discussion

3.1. Variations of pH and ORP

The variations of pH in the simultaneous metal leaching and aerobic digestion experiments at the thermophilic conditions are shown in Fig. 1. The growth of thermophilic sulfur-oxidizing bacteria converting elemental sulfur into sulfuric acid caused the decrease of sludge pH in this study. As indicated in Fig. 1a, that decrease in pH was found during the simultaneous metal leaching and aerobic digestion. The pH after 28 days dropped from 7.3–7.6 to 1.7–3.0 with different solid contents. It was found that the higher pH decreasing rates was observed at lower solid contents. Generally, the biological and chemical oxygen demands are significantly

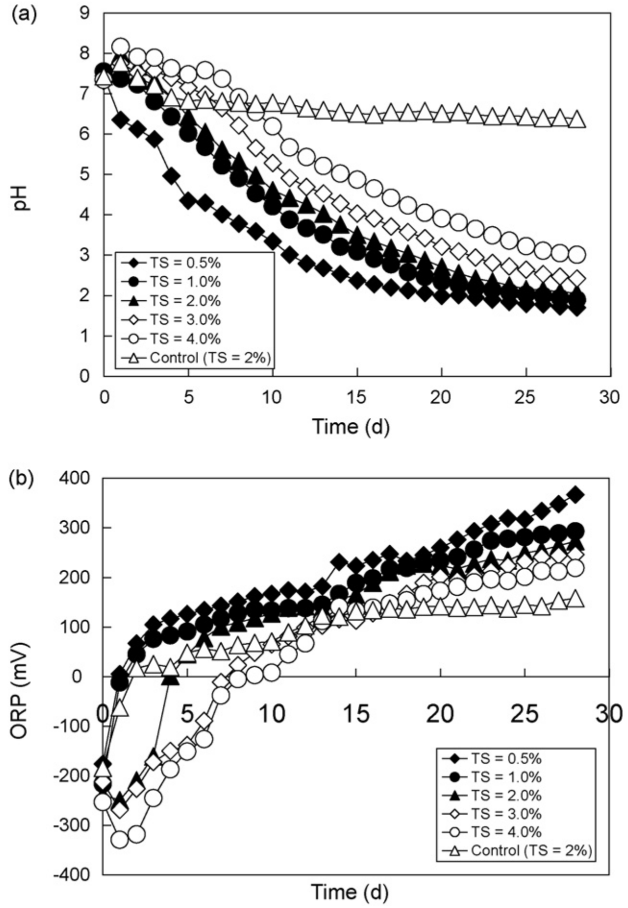

Fig. 1. The variations of (a) pH and (b) ORP in the thermophilic simultaneous metal leaching and aerobic digestion process.

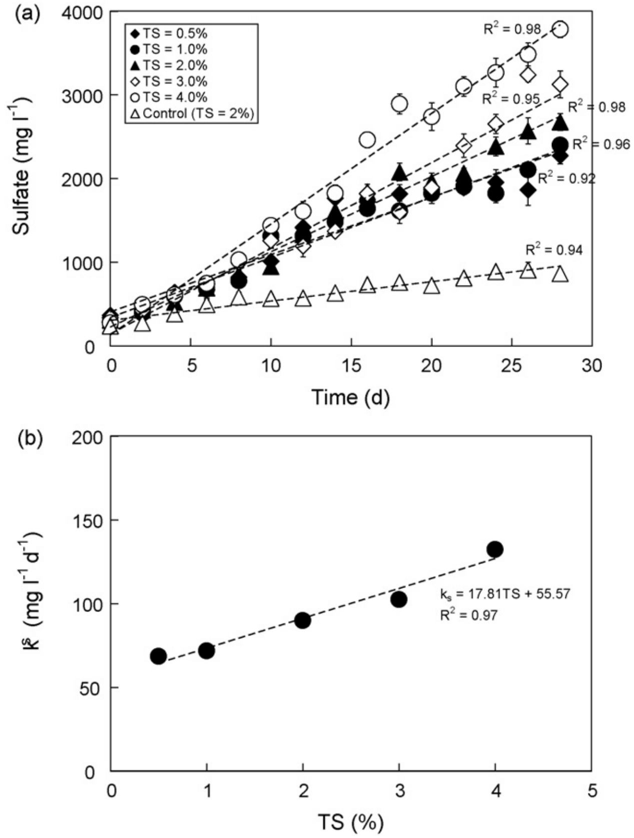

Fig. 2. (a) The variations of sulfate in the thermophilic simultaneous metal leaching and aerobic digestion process. (b) Relationship between sulfate production rate and sludge solid content.

increased with increasing solid contents in the microbial leaching process. Accordingly, the microbial activity was inhibited at high solid contents due to the lack of oxygen [25,26]. Moreover, the sludge with high solid content conceived relatively high buffering capacity in the reactor [16]. Thus the rate for pH decrease was slow at high solids content. On the other hand, the pH only decreased from 7.4 to 6.4 in the control test (without inoculation). This decrease of pH resulted from the production of organic acids during the thermophilic aerobic digestion [27]. Fig. 1b shows the effects of the solid content on the variations of ORP. Generally, the oxidation of sulfur, the acidification of sludge and aeration resulted in an increase of ORP during the microbial leaching process. de Kock et al. [26] demonstrated that a dissolved oxygen (DO) concentration between 1.5 and 4.1 is required for optimal microbial activity during the thermophilic bioleaching process. In general, 0.03–0.2 vvm of air aeration rate was required to maintain the DO concentration at 3 mg l^{-1} during the microbial leaching process [15]. In this study, the air was sparged at a rate of 0.3 vvm and it was enough to ensure good aeration and constant mixing of the sludge. As revealed in Fig. 1b, an increase in ORP was observed in all of the experiments. After 28 days of reaction, ORP increased from (−250)–(−180) mV to 220–370 mV with different solids contents. In the mean time, ORP increased more rapidly in the experiment at lower solid content. However, it was noted that the final value of ORP after 28 day was 160 mV in the control test. It explains that the thermophilic aerobic digestion process and the thermophilic simultaneous metal leaching and aerobic digestion process were occurred at different ORP.

3.2. Variations of sulfate

During the microbial leaching, the elemental sulfur and sulfide were oxidized by bacteria and sulfate was the main final product in the microbial leaching process, therefore the increased of sulfate was observed. The variations of sulfate in the simultaneous metal leaching and aerobic digestion experiments at the thermophilic conditions are shown in Fig. 2a. As evident from the figure, after 28 days the sulfate concentration increased to 2270 mg l^{-1}, 2400 mg l^{-1}, 2680 mg l^{-1}, 3130 mg l^{-1} and 3780 mg l^{-1} at the solid contents of 0.5%, 1.0%, 2.0%, 3.0% and 4.0% (w/v), respectively. The sulfate production rate increased with the increase of the solid contents. This is maybe due to more nutrients (i.e. N and P) at high solid contents more favourable for the bacterial oxidation of sulfur. As shown in Fig. 2a, the sulfate concentration was increased linearly with time [28]. The correlation coefficients (R^2) from the linear regression analysis were all greater than 0.92. The sulfate production rate was determined based on the following equation:

$$\frac{\mathrm{dSO_4}^{2-}}{\mathrm{d}t} = k_\mathrm{s} \qquad (1)$$

where k_s is the rate constant of sulfate production (mg l^{-1} d^{-1}). The rate constants of sulfate production at different solid contents are calculated from the slopes of the plots in Fig. 2a and are represented in Fig. 2b. It was found that the rate of sulfate production exhibited a linear increase with increasing sludge solid contents in this process (R^2 = 0.97). This result was in consistent with another study [29].

3.3. Solubilization of heavy metals

Fig. 4 shows the effect of the solid contents on metal solubilization in the process of the simultaneous metal leaching and aerobic digestion. It has been known that the solubilization of heavy metals in the microbial leaching process was highly associated with pH [8]. Due to the slow rate of acidification in the system (Fig. 1a), a lag phase in metal solubilization was observed at high solid contents. After 28 days, the efficiencies of heavy metals leached from the sludge at different solid contents were 60–93%, 82–99%, 83–98% and 91–97% for Cu, Zn, Mn and Ni, respectively. Because of high affinity of Cu to organic matters in the sludge [30], the lowest efficiency of Cu solubilization was observed at the highest sludge solid content (Fig. 3a). Additionally, it was found that Zn, Mn and Ni were efficiently (>80%) solubilized at the highest solid content (Fig. 3b–d). Overall, the increase in the solid contents decreased the efficiency of metal solubilization. However, the efficiencies of metal solubilization for these four metals were only below 20% in the control test In practice, once the heavy metals are leached from the sludge in the simultaneous metal leaching and aerobic digestion process, heavy metals can be recovered from the leachate by various methods such as precipitation, adsorption, bioadsorption, ion-exchange, solvent extraction and electrochemical technology. However, the precipitation of metals by using chemicals (i.e. lime) is the most simple and widely used method [5]. Meanwhile, the treated sludge is also needed to be revitalised by liming and then, it can be used as soil conditioners or fertilizers.

The rate constants of metal solubilization could be fit to the first-order kinetics as follows:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = k(M_0 - M) \tag{3}$$

and

$$\ln\left(\frac{M_0 - M}{M_0}\right) = -kt \tag{4}$$

where k is the rate constant of metal solubilization (d^{-1}), M_0 and M represent the initial mass (mg) of metal in sludge and mass (mg) of metal in the aqueous phase, respectively. The linear plots of $\ln(M_0 - M/M_0)$ versus time (Fig. 4) indicated that the metal solubilization can be approximated to the first-order kinetics. The rate constants of metal solubilization in the study are obtained from the slopes of the plots and presented in Fig. 5. It was found that the rate of metal solubilization decreased linearly with the increase of solid contents As shown in Fig. 5, the coefficient of TS reflects the effect of solid contents on the rate of metal solubilization In particular, the rate of Zn solubilization was highly influenced by the sludge solid contents. Oppositely, the solid contents had little impact on the rate of Ni solubilization.

3.4. Degradation of solids in sludge

The degradation efficiencies of SS and VSS at different solid contents are illustrated in Fig. 6. Under sludge solid contents of 0.5%, 1.0%, 2.0%, 3.0% and 4.0% (w/v), degradation efficiencies of SS were 75%, 70%, 51%, 46% and 38%, respectively, whereas the degradation efficiencies of VSS were 79%, 74%, 64%, 58% and 54%, respectively. It was found that the degradation efficiencies of solids (SS and VSS) decreased as the solid contents increased in this process. In addition, it was also observed that 43% of SS and 46% of VSS were degraded in the control test at 2% solid content. It is apparent that the degradation efficiencies of SS and VSS in the thermophilic simultaneous metal leaching and aerobic digestion process were higher than those in the traditional thermophilic aerobic digestion (control test).

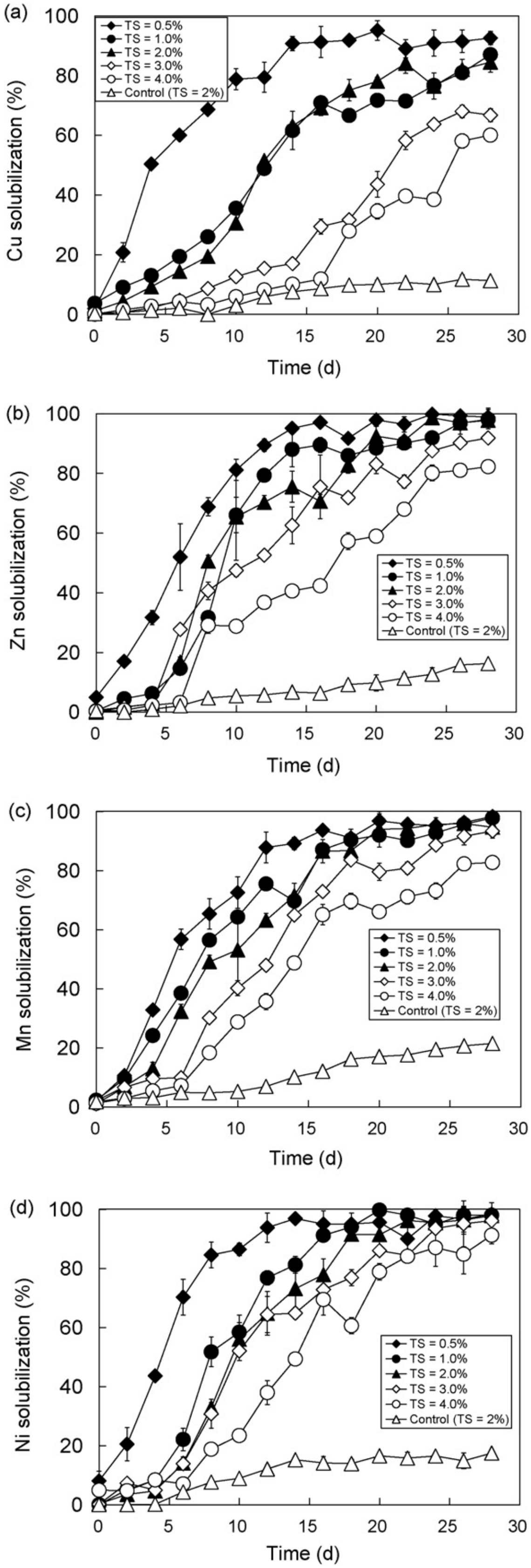

Fig. 3. The metal solubilization in the thermophilic simultaneous metal leaching and aerobic digestion process (a) Cu, (b) Zn, (c) Mn and (d) Ni.

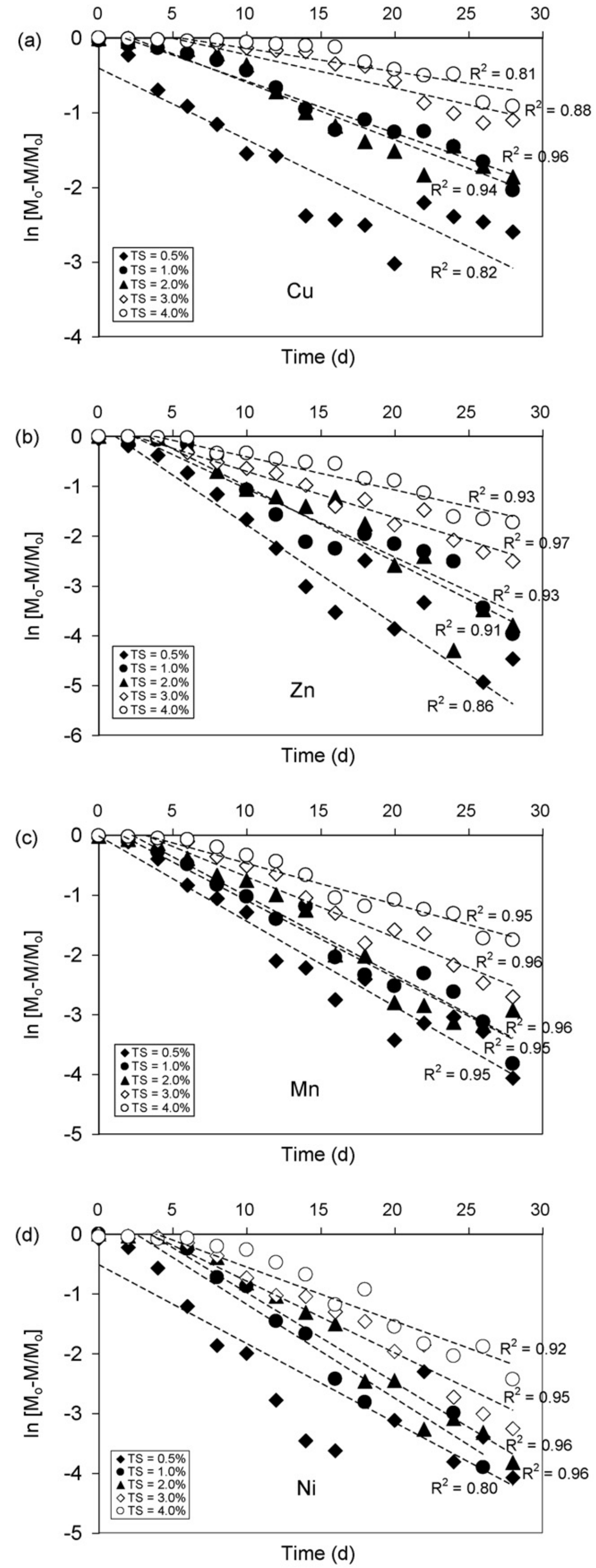

Fig. 4. Plots of $\ln(M_0 - M/M_0)$ versus time for metal solubilization in the thermophilic simultaneous metal leaching and aerobic digestion process (a) Cu, (b) Zn, (c) Mn and (d) Ni.

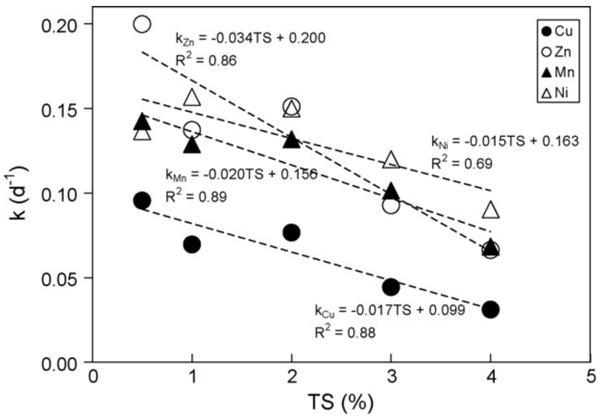

Fig. 5. Relationship between rate of metal solubilization and sludge solid content.

It has been reported that the activities of heterotrophic microorganisms were inhibited when the pH was below 5.6, and thereafter the rate of VSS degradation was slowed down in the aerobic sludge digestion [31]. However, it was observed that the sludge digestion still proceeded when the pH dropped below 5.6 in this study. It indicates that the degradation of solids was mainly contributed by the heterotrophic microorganisms at pH above 5.6, whereas the degradation of solids was primarily caused by the acidification of sulfur-oxidizing bacteria when pH was below 5.6 [29]. Fig. 7 presents the results obtained in the experiment of sludge acidification. It can be observed that the addition of sulfuric acid caused

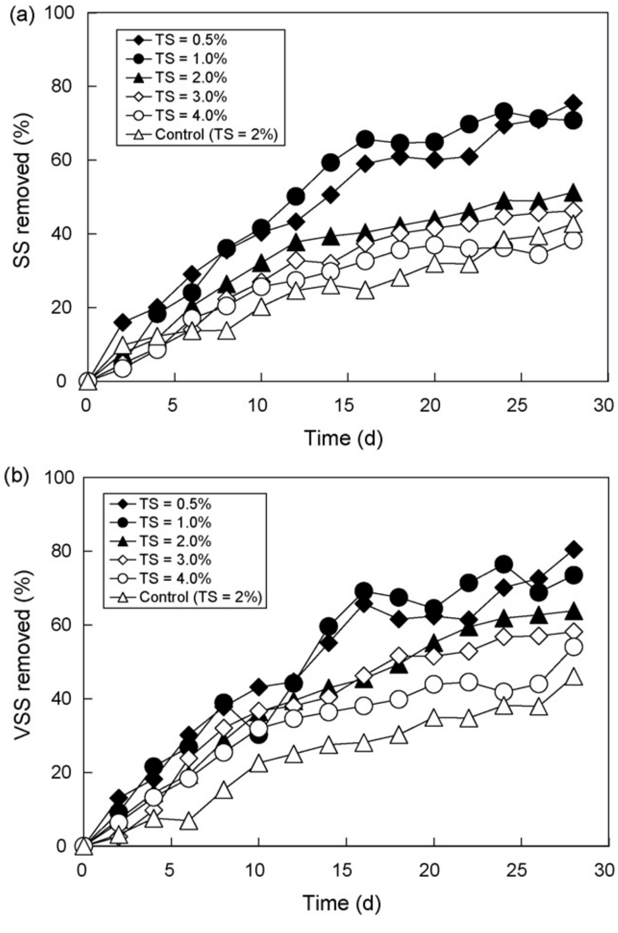

Fig. 6. The degradation of (a) SS and (b) VSS in the thermophilic simultaneous metal leaching and aerobic digestion process.

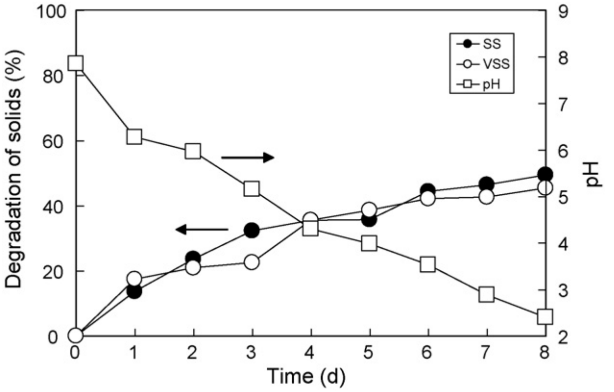

Fig. 7. The degradation of SS and VSS in the experiment of sludge acidification by sulfuric acid.

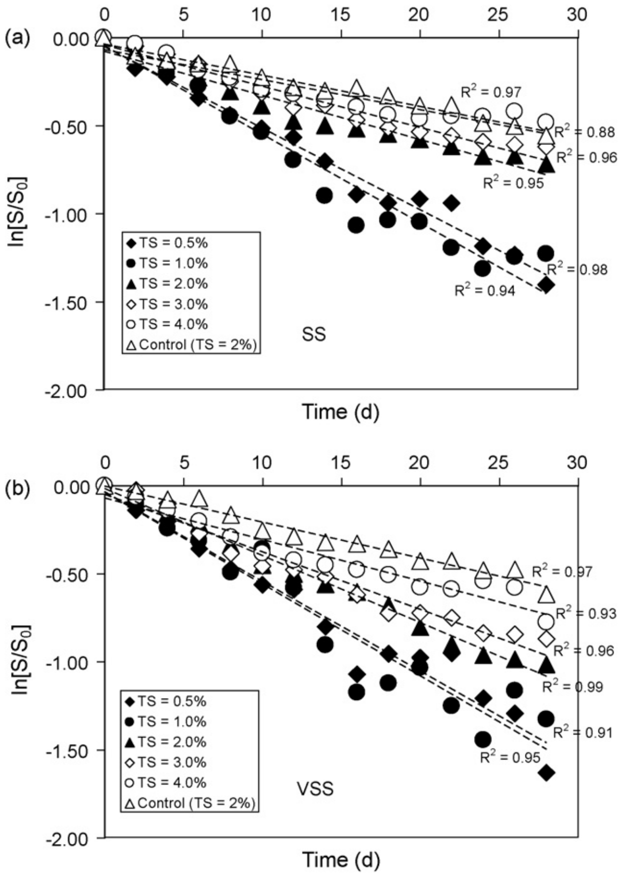

Fig. 8. Plots of ln(S/S_0) versus time for degradation of (a) SS and (b) VSS in the thermophilic simultaneous metal leaching and aerobic digestion process.

the degradation of solids. The removal of SS and VSS were 24% and 21% at the second day (pH 5.9), and then reached 49% and 45% at the 8th day (pH 2.4). This fact confirms that acidification of sludge by sulfuric acid could degrade the solids at 55 °C. As shown in Fig. 6, low sludge solid contents corresponding to, low organic loading rates and high acidification rate could help to achieve high degradation efficiencies of SS and VSS in the reactor operation. The sludge degradation rate of thermophilic simultaneous metal leaching and aerobic digestion process can be described by the following first-order reaction:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -k_\mathrm{d}S \tag{5}$$

where k_d is the rate constant of solid degradation (d^{-1}) and S is the concentration of solids (SS and VSS) in the reactor (mg l^{-1}). The plots of ln(S/S_0) versus time (Fig. 8) were linear for SS and VSS, and suggested the first-order kinetics of the degradation of solids. The rates of solid degradation during the thermophilic simultaneous metal leaching and aerobic digestion process were shown in Fig. 9. As shown in Fig. 9, the solid degradation rate in the thermophilic simultaneous metal leaching and aerobic digestion process was found to be higher than that of control test (thermophilic aerobic digestion). Meanwhile, the rate of solid degradation and solid contents were negatively correlated with each other.

3.5. *Variations of dewaterability and nutrients of sludge*

Sludge dewatering is one of the fundamental steps in sludge treatment because it reduces sludge volume and, consequently, the cost of transporting sludge to its final disposal site. The variations of SRF of sludge are presented in Fig. 10. It was observed that the SRF values decreased from 1.42×10^{14} to 3.06×10^{14} m kg^{-1} to 0.68×10^{13} to 2.87×10^{13} m kg^{-1} after this process. However, the variation of SRF of sludge in the control test was not significant. Generally, the presence of extracellular polymeric substances (EPS) causes the difficulty in sludge dewatering. It has been known that the thermal and acidified pre-treatment of sludge contribute to the degradation of EPS, thus facilitating sludge dewatering [32]. Therefore, the sludge dewaterability was significantly improved by the thermophilic simultaneous metal leaching and aerobic digestion process.

Fig. 11 illustrates the concentrations of total nitrogen, total phosphate and potassium at different solid contents before and after the thermophilic simultaneous metal leaching and aerobic digestion process. As clearly shown in Fig. 11, the release of nutrients occurred in all experiments, including the control test. The percentage of total nitrogen, total phosphate and potassium released from the sludge were 11–18%, 8–35% and 30–38%, respectively. Disregard total phosphate, total nitrogen and potassium released from the sludge through the thermophilic simultaneous metal leaching and aerobic digestion process were slightly more than those through aerobic digestion process (control test) only. The loss of nutrients could be attributed to the highly oxidizing and acidifying conditions during the simultaneous bioleaching and aerobic digestion process [33]. This finding was in agreement with other early studies [33,34]. In spite of the slightly nutrients loss, the issue of odour was also ameliorated by this bioprocess.

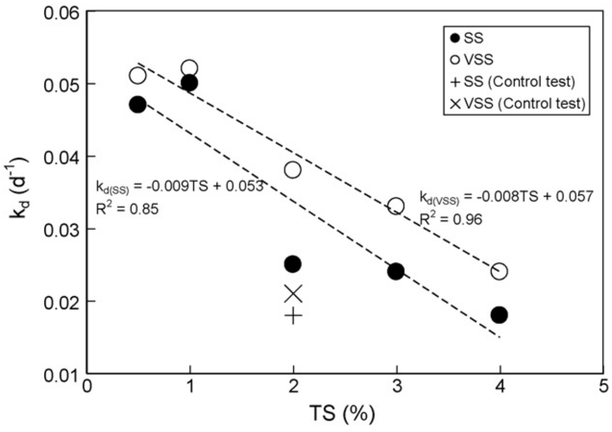

Fig. 9. Relationship between rate of solid degradation rate and sludge solid content.

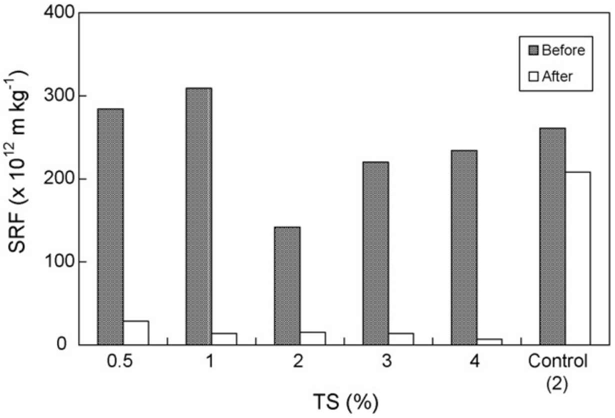

Fig. 10. The sludge dewaterability (SRF) before and after the thermophilic simultaneous metal leaching and aerobic digestion process.

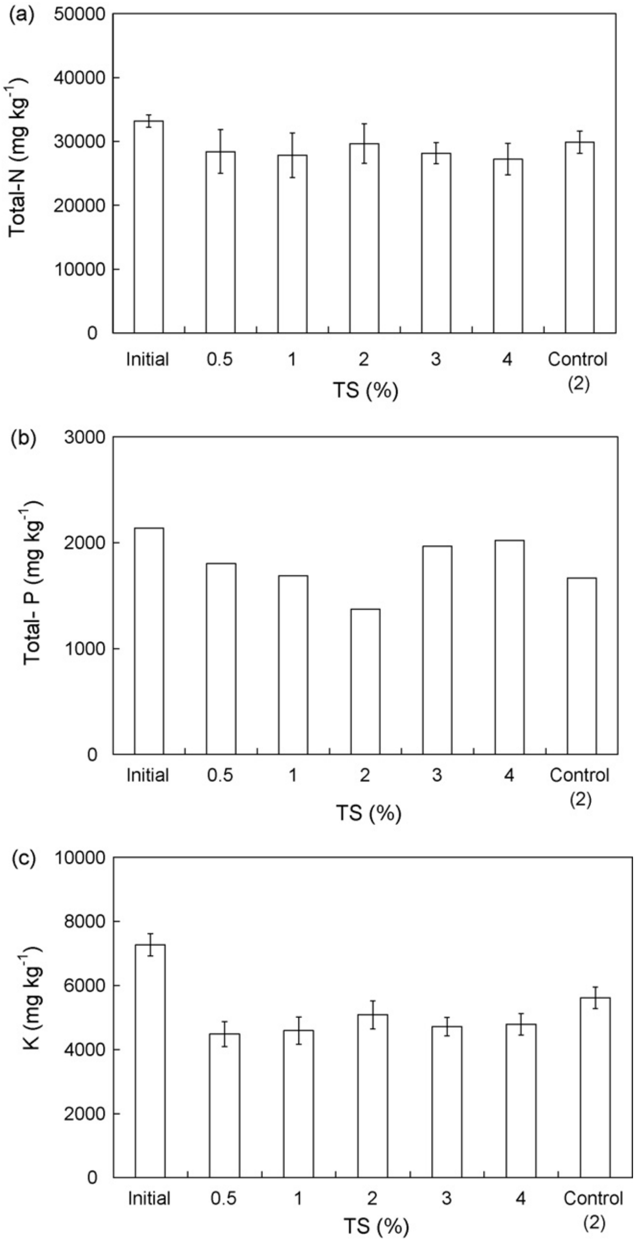

Fig. 11. The concentrations of (a) total nitrogen, (b) total phosphate and (c) potassium in the sludge before and after the thermophilic simultaneous metal leaching and aerobic digestion process.

4. Conclusions

The bioprocess of simultaneously performing the metal leaching and sludge digestion under thermophilic condition was developed in the study. It is one of the promising methods for treating or recycling livestock sludge. Solid loading was one of the most important factors influencing the performance and efficiency of this process. The results of this study indicate that slow decrease rate of pH was due to microbial inhibition and buffering capacity at high solid contents. This trend was also observed at the variations of ORP and sulfate concentration. Except Cu, over 80% of heavy metals were solubilized by this bioprocess. In addition, the efficiency and rate of metal solubilization decreased with increasing solid contents. The thermophilic simultaneous metal leaching and aerobic digestion process also gave a better degradation efficiency of organic matters than that of the traditional thermophilic aerobic digestion. Meanwhile, sludge dewaterability was improved by this bioprocess. Small portion of nutrients (N, P and K) were released from the sludge after this process. Besides the removal of heavy metal and the degradation of organic matter, this process preserved the fertilizer value in sludge. Therefore, the beneficial use of the treated sludge for agricultural land was suggested.

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