



Upgrading volatile fatty acids production through anaerobic co-fermentation of mushroom residue and sewage sludge: Performance evaluation and kinetic analysis

Wei Fang, Panyue Zhang, Tao Zhang, David Carmona Requeson, Morgane Poser

► To cite this version:

Wei Fang, Panyue Zhang, Tao Zhang, David Carmona Requeson, Morgane Poser. Upgrading volatile fatty acids production through anaerobic co-fermentation of mushroom residue and sewage sludge: Performance evaluation and kinetic analysis. *Journal of Environmental Management*, 2019, 241, pp.612-618. 10.1016/j.jenvman.2019.02.052 . hal-04317448

HAL Id: hal-04317448

<https://hal.science/hal-04317448>

Submitted on 1 Dec 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Upgrading volatile fatty acids production through anaerobic co-fermentation of mushroom residue and sewage sludge: Performance evaluation and kinetic analysis

Wei Fang^{a,b}, Panyue Zhang^{b,*}, Tao Zhang^{a,**}, David Carmona Requeson^c, Morgane Poser^d

^a State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, PR China

^b College of Environmental and Engineering, Beijing Forestry University, Beijing, 100083, PR China

^c Department of Biotechnology and Biomedicine, Technical University of Denmark, DK-2800, Lyngby, Denmark

^d National Graduate School of Chemistry, Rennes, France

Keywords:

VFA production
Co-fermentation
Sewage sludge
Spent mushroom compost
C/N ratio

Due to complex inherent structure of lignocellulosic biomass, inefficient hydrolysis and acidification limits fermentative volatile fatty acids (VFA) production of mushroom residues. Meanwhile, the mushroom residues present insufficient nutrient with a high C/N ratio. To solve this issue, anaerobic co-fermentation of cellulose-rich Oyster champost and sewage sludge was tested to enhance the VFA production, and the effect of proportion of mixed substrate was investigated in this study. The results indicated that the sewage sludge yielded higher VFAs than the Oyster champost in single-substrate fermentative system. The maximal VFA yield of 595 mgCOD/gVS_{added} was achieved when the proportion of sewage sludge increased to 50% in the mixed substrate. In the co-fermentation system, the optimal C/N ratio and features of mixed substrate contributed to the enhancement in hydrolysis and acidification in terms of organic solubilization and VFA production, respectively. But the co-fermentation could not increase VFA/SCOD ratio, probably due to the existence of refractory products such as humic-like and protein-like materials. Besides, this co-fermentation system had strong buffer capacity and it was not necessary to dose chemicals to control the system pH for stable VFA production. Acetate was the dominant VFA product in co-fermentation systems. A modified-Logistic model fitted co-fermentation of sludge and Oyster champost well, and presented a faster rate and higher efficiency of VFA production.

1. Introduction

Current situation with increasing resource demand and limited natural resources has directed attention to exploring resource recovery from organic wastes (De Jong et al., 2012). Anaerobic digestion provides an efficient method for resource recovery from organic wastes, where complex polymers are digested and transferred into useful products such as biogas (Van Lier et al., 2008). Such conversion of waste into valuable products also offers an alternative approach to reduce the amount of wastes. Instead of biogas, more exactly methane, volatile fatty acids (VFAs) are recognized as a product with higher added value, because they are widely used as building blocks in chemical industry, such as in the food, pharmaceutical and petrochemical industries. Moreover, harvested VFAs can also be used as carbon source in biological processes of nutrient removal from wastewater (Agler et al.,

2011). More than 6.0 million tons dry sludge every year is produced from wastewater treatment plants (WWTPs) in China (Wu et al., 2016), and the cost of sludge treatment accounts for 30%–50% of the total operation cost in WWTPs. Anaerobic fermentation for VFA production is a possible route for stabilization and resource recovery of sewage sludge. Recently, an increasing number of studies on VFA production from sewage sludge have been carried out, but insufficient C/N ratio limited the hydrolysis of sewage sludge and VFAs production (Esteban-Gutierrez et al., 2018; Lee et al., 2014; Wu et al., 2016), because the C/N ratio of sewage sludge is only around 6–9, much lower than the desired C/N ratio for anaerobic fermentation around 20–30 (Cheng et al., 2016; Li et al., 2011; Zhang et al., 2014).

Co-fermentation has attracted attention because of some unique advantages, such as more balanced nutrients and the dilution of inhibition compounds (Mata-Alvarez et al., 2014). It has been proposed

the co-fermentation of sewage sludge with organic wastes such as lignocellulosic biomass is a feasible option to improve the VFA production (Guo et al., 2016; Huang et al., 2016; Zhou et al., 2013). Guo et al. (2016) investigated the improvement of VFA production from sewage sludge by co-fermentation with straw, and around 3-fold improvement in maximal VFA production was observed compared to that from single sewage sludge fermentation. However, most recent tested lignocellulosic biomass usually presents a high content of lignified component, which limits the accessibility of cellulose and hemicellulose to be digested during anaerobic fermentation (Shirkavand et al., 2017). Therefore, most of these agricultural residues have to be pretreated by mechanical, thermal, chemical methods before co-fermentation (Huang et al., 2016; Zhou et al., 2013; Li et al., 2019). For example, Zhou et al. (2013) carried out co-fermentation of waste activated sludge with corn straw to increase the VFA production. The results showed that the maximal VFA yield increased by 69% with 50% corn straw pretreated by ultrasound of 0.5 kW/L for 10 min. Apparently, an efficient and sustainable pretreatment method should be conducted with a maximal VFA productivity and a minimal input of energy and/or chemical reagents, otherwise, the extensive consumption of energy and/or chemicals will restrict their application due to the increase of production cost and operation complexity, as well as potential negative impacts on microorganisms.

Therefore, selection of the suitable agricultural residues with high C/N ratio and low resource input for pretreatment is beneficial to the VFA production from co-fermentation. In addition to above mentioned substrates, Oyster champost, a lignocellulosic byproduct of commercial mushroom industry, may be a promising candidate for VFA production due to its high content of cellulose, hemicellulose and relatively low content of lignin. Besides, the mushroom champost is decomposed and permeated by fungal mycelia during mushroom cultivation, therefore, it is more digestible compared with other lignocellulosic biomass (Fang et al., 2016; Lin et al., 2015). Unfortunately, due to limited sustainable disposal strategies, most champost are discarded as low value products in China (Shi et al., 2014). In the view of improving treatment and resource recovery from Oyster champost, it is also necessary to find an effective approach to catch up with the treatment capacity of champost. It is hypothesized that the addition of Oyster champost into sewage sludge may improve C/N ratio and prevent the negative impacts of added lignin on the fermentative system. However, so far there is no information reported about the co-fermentation of Oyster champost and sewage sludge for improving the VFA production.

Based on above considerations, the added cellulose-rich champost was expected to increasing an efficiency of co-fermentation. The primary objective of this study was to investigate the feasibility of co-fermentation of Oyster champost and sewage sludge for improving the VFA production. Secondly, the effect of feedstock proportion on hydrolytic solubilization of organics, VFA yield and composition was explored. The pH variations and the release of ammonium and phosphate were also observed. Finally, the kinetics of VFA production was analyzed by Logistic-based model.

2. Materials and methods

2.1. Characteristics of Oyster champost and sewage sludge

The Oyster mushroom champost was obtained from one mushroom research plant. The Oyster champost was dried in oven at 70 °C until a constant weight and then stored at room temperature prior to use. The thickened sewage sludge used in this study was taken from a local wastewater treatment plant, which has a treatment capacity of 1.3 million pollution equivalents. Anaerobic sludge used as inoculum was taken from the mesophilic anaerobic digester in the same plant. These two fermentation materials were stored at 4 °C for further use. The main characteristics of these materials are displayed in Table S1.

2.2. Batch test of anaerobic fermentation

Batch tests for VFA production were conducted in anaerobic test bottles with a working volume of 400 ml at 30 °C. In each test bottle, the initial TS concentration of substrate was set as 5% and the inoculum amount was determined by setting an inoculum to substrate ratio of 2 on VS weight. To inhibit the activity of methanogens, 2-Bromoethanosulphate of 19 mmol/L was added in all the test systems before experiments (Fang et al., 2018). All chemical reagents used in this study were purchased from Sigma-Aldrich.

To investigate the effect of feedstock proportion on the VFA production, the mixed substrate contents labelled as sludge/champost ratio of 100%:0, 75%:25%, 50%:50%, 25%:75% and 0:100% (Table S2). A sludge/champost ratio of 100%:0 and 0:100% represented only sewage sludge and Oyster champost as single substrate, respectively.

2.3. Analytic methods

TS and VS were determined on weight base (g/kg) according to the Standard Methods (APHA, 2005). About 15 g samples was put in aluminum dish at 105 °C for 8 h to determine the TS. After recording the weights, the samples were kept in an oven at 600 °C for 2 h to determine the VS. The C/N ratio was calculated by the ratio of total carbon and total nitrogen weight, which were detected by element analyzer (vario MACRO cube, Elementar, German). For SCOD, $\text{NH}_4^+ - \text{N}$, $\text{PO}_4^{3-} - \text{P}$ and VFA measurements, the samples were centrifuged at 12,000 r/min at 4 °C for 15 min, and then filtered by syringe membrane with 0.45 μm (Whatman, Germany). The SCOD, $\text{NH}_4^+ - \text{N}$ and $\text{PO}_4^{3-} - \text{P}$ concentration in fermentation broth were measured using photometric cell tests (Hach-Lange, Germany). The details of VFA measurement was displayed in the Supporting Materials.

2.4. Kinetic modeling of VFA production

Logistic-based model was applied to fit the observed VFA production in this study, which is shown as Eq. (1) (Fang et al., 2017):

$$\frac{dC_{\text{VFA}}}{dt} = \mu C_{\text{VFA}} \left(1 - \frac{C_{\text{VFA}}}{C_{\text{max}}} \right) \quad (1)$$

where t refers to the fermentation time (d), C_{VFA} is the VFA concentration, C_{max} is maximum VFA concentration, and μ represents the maximal specific VFA production rate.

3. Results and discussion

3.1. VFA production during anaerobic fermentation

3.1.1. VFA production

VFA yield is an obvious index to evaluate anaerobic fermentation efficiency. The VFA yield in terms of COD under different feedstock proportions during anaerobic fermentation is illustrated in Fig. 1. As shown in Fig. 1, the VFA yield first increased quickly in all fermentation systems and gradually began to a plateau. For single-substrate fermentation systems, the sewage sludge showed obviously higher VFA accumulation compared to that of Oyster champost after 20-day fermentation. The maximal VFA yield of sewage sludge was 521 mgCOD/gVS_{added} on the 18th day, which was 19.5% higher than that of Oyster champost (436 mgCOD/gVS_{added}). The VFA yield was within the widely reported range of VFA production from sewage sludge (Ferreiro and Soto, 2003; Higgins et al., 2017; Yuan et al., 2011). For co-fermentation system, the maximal VFA yield with a sludge/champost ratio of 75%:25%, 50%:50% and 25%:75% was 512, 596 and 505 mgCOD/gVS_{added}, respectively.

The results in this study indicated that the sewage sludge had a higher ability of VFA production than the Oyster champost due to the higher biodegradability of sewage sludge than that of lignocellulosic

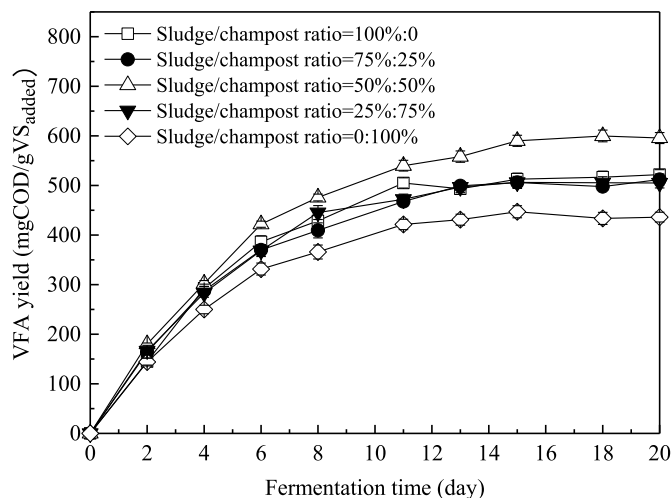


Fig. 1. Effect of feedstock proportion on VFA yield during anaerobic fermentation.

biomass (Zhou et al., 2014). Hence, it is reasonable that more sewage sludge addition in the mixed substrate would be beneficial to the increase of VFA yield during co-fermentation. The results also consisted with that the partial addition of sewage sludge in Oyster champost improved the VFA yield compared to single-substrate fermentation of Oyster champost. However, it was not always positively correlated with the sewage sludge addition in the feedstock. When the sludge/champost ratio was 50%:50%, the maximal VFA yield was obtained, which was approximately 37% and 14% higher than that of single-champost and single-sludge fermentation. When the sludge/champost ratio was over 50%:50%, less VFAs were produced. The other factors might also influence the VFA production except the substrate ratio, such as the substrate characteristics and C/N ratio. It is worth noticing that the addition of sewage sludge in champost changed initial C/N of mixed substrate, which might be provided more suitable C/N ratio for microbe growth and metabolism (Rughoonundun et al., 2012). Generally, a C/N ratio range of 20–30 is considered as the optimum condition for anaerobic fermentation (Rughoonundun et al., 2012; Zhang et al., 2014). The C/N ratio for a sludge/champost ratio of 100%:0, 75%:25%, 50%:50%, 25%:75% and 0%:100% was 6.0, 12.7, 19.3, 26.0 and 32.6, respectively. Therefore, the addition of sewage sludge could make C/N ratio was closer to the optimal value. When the sludge/champost ratio was 25%:75%, the initial C/N (26.0) of this system was indeed more suitable than that (19.3) with a higher sludge/champost ratio of 50%:50%, however, the maximum VFA yield was achieved at the sludge/champost ratio of 50%:50%. Possibly the more VFA production was attributed to more easily biodegradable organic matters in sewage sludge rather than the suitable initial C/N.

Table 1 shows the comparison of VFA yield in this study with the published data from co-fermentation of sewage sludge with other organic matters. The maximal VFA yield of 596 mgCOD/gVS_{added} in this study was much higher than that from other combination of sewage

sludge with agriculture wastes and alkaline pretreated bagasse. The lower VFA yield in this study than the fermentation of sludge with kitchen wastes was probably due to the fact that the kitchen wastes consist of more easily biodegradable components than the lignocellulosic biomass (Vavilin et al., 2008).

3.1.2. VFA composition during fermentation

In this study, acetate, propionate, butyrate, valerate and hexanate were all detected in all fermentation systems. Table 2 summaries the percentage of individual VFA accounting for total VFAs by the end of anaerobic fermentation. The results indicated that the acetate was the dominant products accounting for 36%–39% in all fermentation systems. And the individual VFA percentage was in the sequence of acetate > propionate > butyrate > valerate > hexanate.

This result coincided with the results from co-fermentation of sewage sludge with rice straw and bagasse (Kim et al., 2012; Liu et al., 2016; Rughoonundun et al., 2012). The percentage of propionate significantly decreased with the increase of sewage sludge addition, and the decrease was about 12%. However, the percentage of butyrate and valerate increased by about 4% and 8% with the increase of sewage sludge addition. The results can be probably explained by reduction in chain elongation during fermentation process because of the change of C/N ratio (Agler et al., 2011). The initial C/N ratio can affect the metabolic pathways of microbe for VFA production (Lee et al., 2014). With a high C/N ratio, the main pathway of propionate production was converted into the glycolytic pyruvate pathway (Agler et al., 2011; Rughoonundun et al., 2012). When the C/N ratio decreased, the acetate was mainly produced by the Stickland reaction from amino acids. Besides, all the system showed a lowest hexanate production, which accounted for less than 1.5% in the total VFAs.

3.2. Discussion on possible mechanisms

3.2.1. SCOD variation during co-fermentation

Anaerobic digestion is a multi-stage process which consists of hydrolysis, acidogenesis, acetogenesis and methanogenesis (Fang et al., 2014). In the hydrolysis step, insoluble organic materials and higher molecular compounds are degraded into smaller and soluble organic materials, which are further transformed into various VFAs, H₂ and CO₂ during the acidogenesis. SCOD is an important and effective parameter to evaluate the release of organics from substrate to the liquid phase (Ma et al., 2017; Wang et al., 2018). As shown in Fig. 2, the SCOD in all systems significantly increased in the first two days, and then slowly increased or remained steady till the end of anaerobic fermentation. The increased SCOD was possibly attributed to the release of protein, polysaccharide and lipid from sewage sludge, and cellulose, hemicellulose from Oyster champost (Huang et al., 2016; Wang et al., 2018). Apparently, the feedstock proportion influenced the release of organic matter from the substrates. For the single-substrate fermentation, it's obvious that the champost released less organic matter and led to lower efficiency of hydrolysis, compared to the sewage sludge. After 20-day anaerobic fermentation, the maximum SCOD of sewage sludge and Oyster champost was 15,873 and 14,450 mg/L, respectively. The

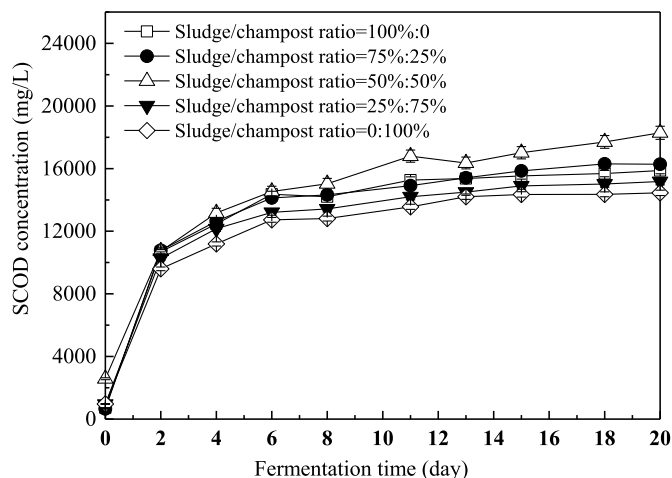
Table 1
Comparison of VFA yield from sludge with different organic substrates.

Substrate	Average VFA yield	Operation conditions	References
Dewatered sludge + kitchen waste	392 mg/gVS _{added}	Batch test, 35 °C, initial pH = 7.0 ± 0.1, fermentation time = 9 d	Hong and Haiyun (2010)
Waste activated sludge + agriculture wastes	487 mgCOD/gVS _{added}	Continuously stirred-tank reactors, mesophilic condition, pH = 10.0 ± 0.5, Sludge retention time = 5 d	Guo et al. (2016)
Waste activated sludge + kitchen waste	670 mgCOD/gVS _{added}	Semi-continuous-flow reactors, 37 °C, pH = 8.0, fermentation time = 6 d	Chen et al. (2013)
Waste activated sludge + pretreated bagasse	360 mg/gVS _{added}	Batch test, 55 °C, pH = 7.0, fermentation time = 20 d	Rughoonundun et al. (2012)
Thickened sludge + Oyster champost	596 mgCOD/gVS _{added}	Batch test, 30 °C, without pH control, fermentation time = 18 d	This study

Table 2

Individual VFA percentage of anaerobic fermentation with different sludge/champost ratios.

Sludge/champost ratio	100%:0	75%:25%	50%:50%	25%:75%	0:100%
Acetate (%)	39.17 ± 0.89	39.71 ± 1.22	37.21 ± 0.96	36.88 ± 0.95	38.85 ± 0.85
Propionate (%)	21.88 ± 0.53	25.92 ± 0.59	30.37 ± 0.62	29.08 ± 0.71	33.81 ± 0.62
Butyrate (%)	19.76 ± 0.46	18.21 ± 0.43	19.40 ± 0.42	18.79 ± 0.53	15.78 ± 0.52
Valerate (%)	17.79 ± 0.56	15.36 ± 0.49	11.82 ± 0.52	13.91 ± 0.58	9.31 ± 0.37
Hexanate (%)	1.43 ± 0.37	1.08 ± 0.35	1.19 ± 0.27	1.32 ± 0.35	0.57 ± 0.12

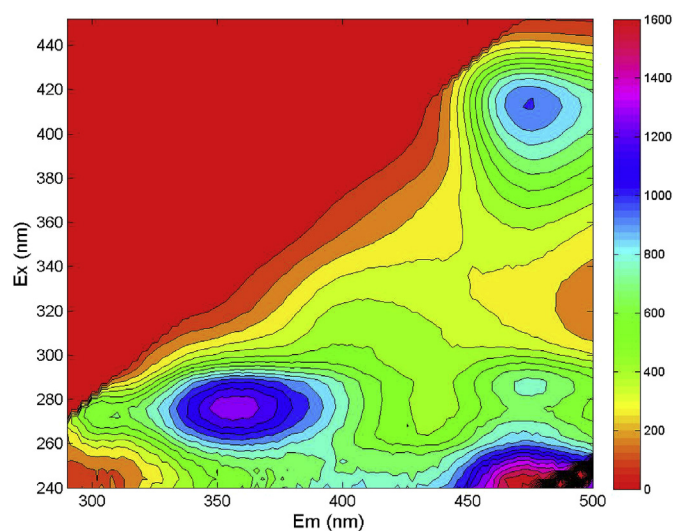
**Fig. 2.** Effect of feedstock proportion on SCOD concentration during anaerobic fermentation.

complex structure of lignocellulosic biomass, especially the existence of a large amount of lignin in Oyster champost, resulted in the resistance to hydrolysis in this study (Fang et al., 2017). On the other hand, protein and polysaccharide, as main components of sewage sludge, were more easily and quickly biodegraded than the cellulose and hemicellulose in Oyster champost (Fang et al., 2017; Mata-Alvarez et al., 2014).

In the co-fermentation systems, the SCOD increased with the addition of sewage sludge, and the maximum SCOD of 18,288 mg/L was achieved with a sludge/champost ratio of 50%:50%, which was 13.2% and 26.6% higher than that of single-sludge and single-champost fermentation, respectively. The more hydrolysates could offer more organic matters for further acidification process and lead to higher VFA production. Previous studies have also reported that co-fermentation of lignocellulosic biomass, such as corn straw, bagasse with sewage sludge can improve the solubilization of substrates (Rughoonundun et al., 2012; Zhang et al., 2016). However, the SCOD with a sludge/champost ratio of 75%:25% decreased, which might be attributed to the decrease of C/N ratio of mixed substrate to 12.7. Chen et al., (2013) investigated the enhancement of VFA production by co-fermentation of waste activated sludge and kitchen wastes, and also found that the organic solubilization was lower at a C/N ratio of 14 than that at a C/N ratio of 22.

3.2.2. VFA/SCOD ratio variation during co-fermentation

VFA/SCOD ratio can reflect the conversion extent of SCOD to VFA during anaerobic fermentation. After anaerobic fermentation, the VFA concentrations with a sludge/champost ratio of 100%:0, 75%:25%, 50%:50%, 25%:75% and 0:100% was 5202, 5019, 5904, 5058 and 4548 mg/L, correspondingly, the VFA/SCOD was 32.8%, 29.8%, 32.3%, 33.3% and 31.5%, respectively. This results revealed that co-fermentation could not increase VFA/SCOD ratio, although it increased the VFA concentration in the fermentation broth and VFA yield. Therefore, there were large fraction components in fermentation broth which could not be converted to VFAs during anaerobic fermentation.

**Fig. 3.** Three-dimensional fluorescence pattern of fermentation broth with a sludge/champost ratio of 50%:50% by the end of anaerobic fermentation.

To further characterize the organics in fermentation broth, EEM analysis was carried out. As shown in Fig. 3, three peak were detected in the fermentation broth with a sludge/champost ratio of 50%:50% after anaerobic fermentation. According to Chen et al., (2003), these detected peaks corresponded to tryptophan and protein-like (Ex/Em = 270 nm/350 nm), fulvic-like acids (Ex/Em = 250 nm/460 nm) and humic-like (Ex/Em = 400 nm/460 nm), respectively. It seemed that the residual organics such as protein-like and humic-like components had poor biodegradability, and even negatively impacted the VFA production (Gonzalez et al., 2018). One of the evidences is that the residual proteins after sludge fermentation were mainly detected as outer membrane proteins, which were mainly from Gram-positive bacteria and difficult to be degraded (Tan et al., 2012). Yuan et al. (2011) demonstrated that around 54% of proteins could not be converted to VFAs in the acidogenic stage during anaerobic sludge fermentation. Yin et al., (2016) also reported that poor biodegradability of protein-like materials in the residual fermented sludge limited the further VFA production from sludge. Furthermore, the humic-like substances showed almost no anaerobical biodegradability (Zahmatkesh et al., 2018). Meanwhile, the existence of humic-like substances could decrease the substrate biodegradation through immobilization enzymes such as protease, cellulase during anaerobic digestion process (Dang et al., 2016; Gonzalez et al., 2018).

3.2.3. pH and release of ammonium and phosphate

pH is another important influencing parameter in anaerobic fermentation. Fig. 4 shows the pH variation during anaerobic fermentation. As shown in Fig. 4, the initial pH increased with increasing the sludge addition in the mixed substrate. The pH changes in all fermentation systems were similar: quickly dropping within the first 2 days and then slowly decreasing in the remaining digestion period. After 20-day anaerobic fermentation, the pH values reduced to 6.18, 6.06, 6.04, 5.95 and 5.89 with a sludge/champost ratio of 100%:0, 75%:25%,

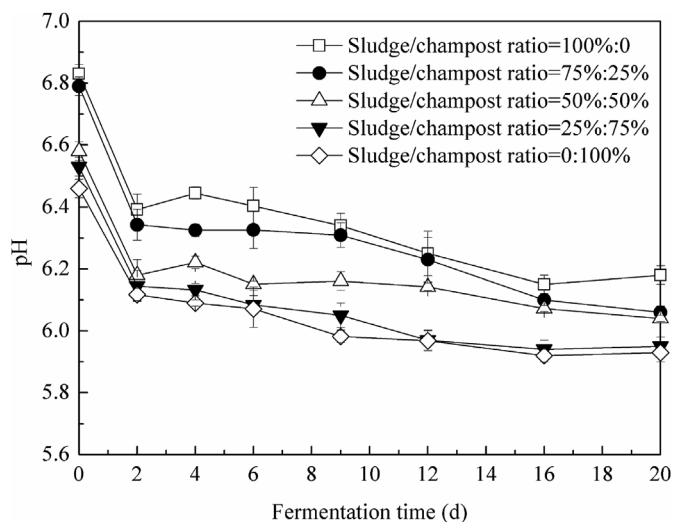


Fig. 4. pH variation during anaerobic fermentation.

50%:50%, 25%:75% and 0:100%, respectively, probably due to the VFA accumulations (Fang et al., 2018).

Moreover, as also shown in Fig. 4, the pH of single-substrate champost decreased lower than 6.0 after 12-day anaerobic fermentation. This result could explain why the SCOD of single-champost fermentation did not significantly increase after 12-day anaerobic fermentation (as shown in Fig. 2). It has been reported that the activities of cellulolytic bacteria and hydrolysis of lignocellulosic biomass were totally inhibited at a pH lower than 6.0 (Mould et al., 1983; Russell and Wilson, 1996). Besides, it is also worthy noticing that the pH of 5.95 at a sludge/champost ratio of 25%:75% was lower than 6.0, which could inhibit the hydrolysis of lignocellulosic biomass (Russell and Wilson, 1996). The lower pH might be another reason for the lower VFA production at a sludge/champost ratio of 25%:75% than that at a sludge/champost ratio of 50%:50%. On the other hand, the pH of single-sludge fermentation was always higher than that of single-champost fermentation, indicating that the sewage sludge had better buffer capacity than the Oyster champost. In the co-fermentation systems, the system pH was always higher than 6.0 during the whole anaerobic fermentation, which met the minimum pH requirement for organic hydrolysis. Hence, the co-fermentation system had enough buffer capacity for anaerobic fermentation, and it was not necessary to dose chemicals to keep a stable pH for VFA production.

Ammonia released from the substrate during hydrolysis can act as a pH buffer. The initial ammonium concentrations in all tests were in a range from 80 to 110 mg/L at a pH below 7.0. Hence, the free ammonia concentration was not enough high to inhibit anaerobic digestion process (Appels et al., 2008). After anaerobic fermentation, the ammonium concentrations of systems increased with the increase of sewage sludge addition, and reached about 2660, 2380, 2210, 2180 and 1820 mg/L with a sludge/champost ratio of 100%:0, 75%:25%, 50%:50%, 25%:75% and 0:100%, respectively. More ammonium might be mainly released from the degradation of proteins and amino acids of sewage sludge (Nagase and Matsuo, 1982). Interestingly, the variation of ammonium concentration showed similar trend with pH variations with different sludge proportions. Probably the suitable increase of ammonium concentration provided a better buffer capacity for the co-fermentation systems, ensuring that the system pH was in a suitable range during anaerobic fermentation process. Besides, after anaerobic fermentation phosphate concentration of systems increased with the increase of sewage sludge addition, and was observed approximately 570, 480, 470, 480 and 390 mg/L with a sludge/champost ratio of 100%:0, 75%:25%, 50%:50%, 25%:75% and 0:100%, respectively. The higher phosphate concentration with addition of sewage sludge was probably

contributed to biodegradation of phosphorus compounds, which was stored as polyphosphates in sewage sludge, such as cell wall and lipid.

The excessive ammonium and phosphate in fermentation broth may influence the VFA recovery and the quality of subsequent products (Lee et al., 2014). The ammonium and phosphate concentration with a sludge/champost ratio of 50%:50% were higher than those of single-champost fermentation, but about 17% and 18% lower than those of single-sludge fermentation, respectively. Considering the purpose of VFA production in this study, the co-fermentation with a sludge/champost ratio of 50%:50% produced maximal VFA yield with the lowest release of ammonium and phosphate. The optimal substrate proportion of sludge/champost ratio = 50%:50% for co-fermentation should be selected. In the view of resource recovery of nitrogen and phosphorus from fermentation broth, the simultaneous recovery of ammonium and phosphate in a form of struvite or dry ammonium can be considered as a competitive method, and the products can be utilized as a fertilizer (Liu et al., 2016).

3.3. Kinetic modeling of co-fermentation

In this study, the modified-Logistic model was used to assess VFA production during anaerobic fermentation with different sludge/champost ratios. According to VFA concentration obtained from experiments, we fitted and calculated various kinetic parameters by Origin 8.0. The relevant results are presented in Table 3 and Fig. 5. It revealed that the VFA production from all fermentation systems were well fitted by modified-Logistic model with a R^2 from 0.9940 to 0.9994. The VFA production from champost was improved by co-fermentation with sewage sludge addition in different proportions, and the maximum VFA production was 6003 mg/L was obtained with a sludge/champost ratio of 50%:50%. The high maximal specific VFA production rate of 4.04 with a sludge/champost ratio of 50%:50% indicated a faster rate and higher efficiency of VFA production. The modeling results indicated that the co-fermentation with sewage sludge addition was significantly enhanced the VFA production.

4. Conclusions

This study showed hydrolysis and VFA production from cellulose-rich Oyster champost was successfully enhanced by the addition of sewage sludge. The maximal VFA yield of 596 mgCOD/gVS_{added} was achieved with a sludge/champost ratio of 50%:50%, which was approximately 37% and 14% higher than that of single-champost and single-sludge fermentation. The Oyster champost and sewage sludge played a critical role in regulation initial C/N rate for improving hydrolysis rate and biodegradation, as well as variations of VFA composition during anaerobic fermentation. The maximum SCOD in all fermentation systems was obtained with a sludge/champost ratio of 50%:50%, which was 13.2% and 26.6% higher than that of single-sludge and single-champost fermentation, respectively. The addition proportion of sewage sludge did not change fermentative type, and the acetate was dominant VFA product accounting for 36%–39%. During the co-fermentation process, ammonium and phosphate were released

Table 3

Main fitted kinetics parameters of Logistic model with different sludge/champost ratios.

Sludge/champost ratio	Logistic model		
	C_{max} (mg/L)	μ (d^{-1})	R^2
100%:0	5242 ± 80.5	3.98 ± 0.29	0.9940
75%:25%	5196 ± 78.9	4.09 ± 0.28	0.9993
50%:50%	6003 ± 96.3	4.04 ± 0.33	0.9970
25%:75%	4971 ± 78.8	3.66 ± 0.18	0.9952
0:100%	4631 ± 69.2	3.75 ± 0.23	0.9994

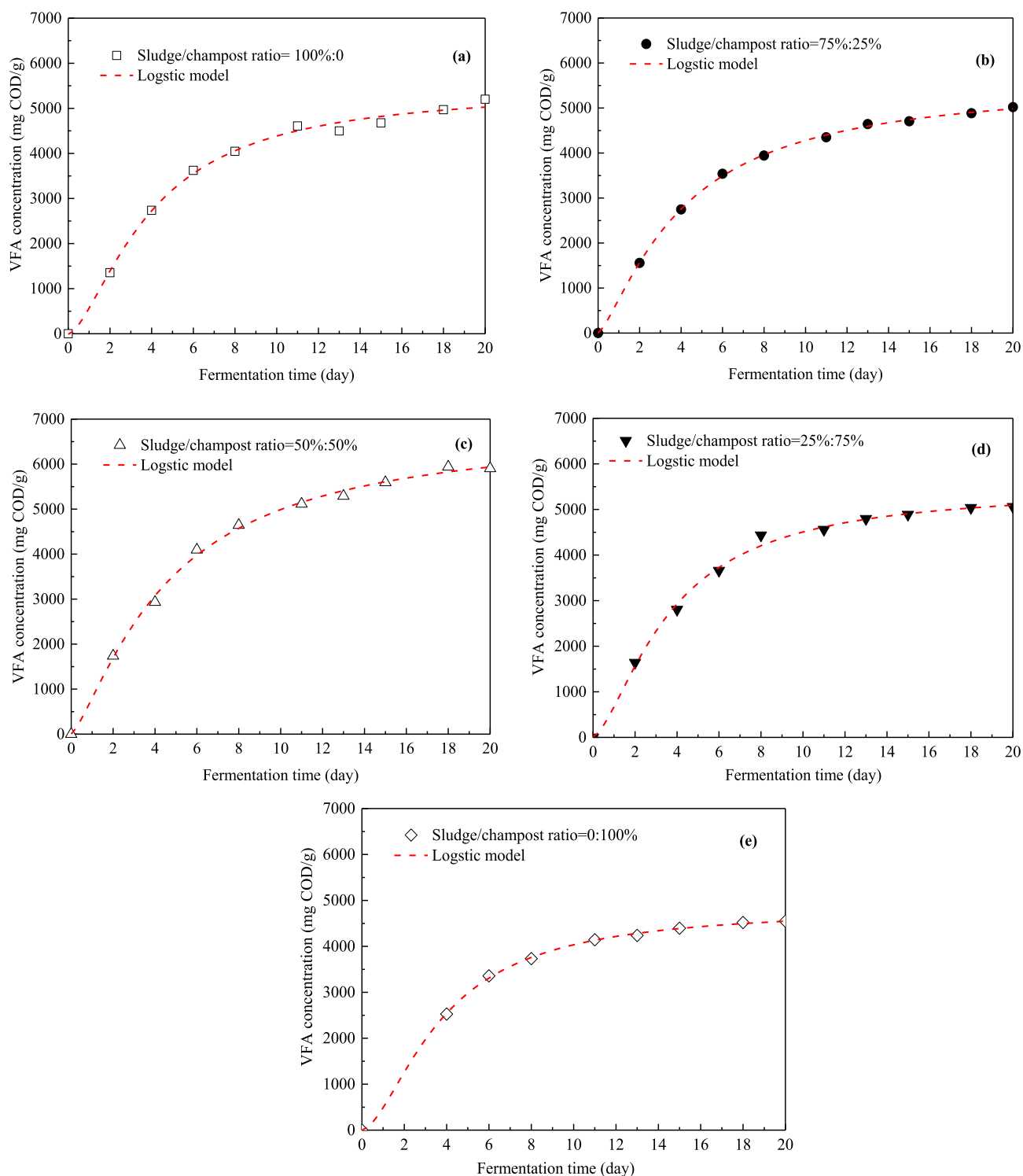


Fig. 5. Fitting curves with Logistic model for VFA production with different sludge/champost ratios.

because of degradation of organic matters in sewage sludge. A Logistic-based model well described the VFA production process, showing that the co-fermentation with sewage sludge addition was significantly enhanced the VFA production from Oyster champost. The above co-fermentation process provides a promising way to simultaneously recover the high-value bioproducts from cellulose-rich Oyster champost and sewage sludge.

Acknowledgments

The authors acknowledge the National Natural Science Foundation of China (51578068) and the “One Thousand Talent Plan” Youth Program for funding this research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://>

References

- Agler, M.T., Wrenn, B.A., Zinder, S.H., Angenent, L.T., 2011. Waste to bioproduct conversion with undefined mixed cultures: the carboxylate platform. *Trends Biotechnol.* 29 (2), 70–78.
- APHA, 2005. Standard Methods for the Examination of Water and Wastewater. Am. Public Health Assoc. APHA Wash., DC, USA.
- Appels, L., Baeyens, J., Degreève, J., Dewil, Raf, 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Prog. Energy Combust.* 34 (6), 755–781.
- Chen, W., Westerhoff, P., Leenheer, J.A., Booksh, K., 2003. Fluorescence excitation-emission matrix regional integration to quantify spectra for dissolved organic matter. *Environ. Sci. Technol.* 37 (24), 5701–5710.
- Chen, Y., Luo, J., Yan, Y., Feng, L., 2013. Enhanced production of short-chain fatty acid by co-fermentation of waste activated sludge and kitchen waste under alkaline conditions and its application to microbial fuel cells. *Appl. Energy* 102 (0), 1197–1204.
- Cheng, J., Ding, L.K., Lin, R.C., Yue, L.C., Liu, J.Z., Zhou, J.H., Cen, K.F., 2016. Fermentative biohydrogen and biomethane co-production from mixture of food waste and sewage sludge: effects of physiochemical properties and mix ratios on fermentation performance. *Appl. Energy* 184, 1–8.
- Dang, Y., Lei, Y., Liu, Z., Xue, Y., Sun, D., Wang, L.-Y., Holmes, D.E., 2016. Impact of fulvic acids on bio-methanogenic treatment of municipal solid waste incineration leachate. *Water Res.* 106, 71–78.
- De Jong, E., Higson, A., Walsh, P., Wellisch, M., 2012. Bio-based chemicals value added products from biorefineries. IEA Bioenergy 132–135 Task42 Biorefinery.
- Esteban-Gutierrez, M., Garcia-Aguirre, J., Irizar, I., Aymerich, E., 2018. From sewage sludge and agri-food waste to VFA: individual acid production potential and up-scaling. *Waste Manag.* 77, 203–212.
- Fang, W., Zhang, P., Zhang, G., Jin, S., Li, D., Zhang, M., Xu, X., 2014. Effect of alkaline addition on anaerobic sludge digestion with combined pretreatment of alkaline and high pressure homogenization. *Bioresour. Technol.* 168 (0), 167–172.
- Fang, W., Zhang, P.Y., Gou, X.Y., Zhang, H.B., Wu, Y., Ye, J., Zeng, G.M., 2016. Volatile fatty acid production from spent mushroom compost: effect of total solid content. *Int. Biodeterior. Biodegrad.* 113, 217–221.
- Fang, W., Ye, J., Zhang, P., Zhu, X., Zhou, S., 2017. Solid-state anaerobic fermentation of spent mushroom compost for volatile fatty acids production by pH regulation. *Int. J. Hydrogen Energy* 42 (29), 18295–18300.
- Fang, W., Zhang, P.Y., Zhang, X.D., Zhu, X.F., van Lier, J.B., Spanjers, H., 2018. White rot fungi pretreatment to advance volatile fatty acid production from solid-state fermentation of solid digestate: efficiency and mechanisms. *Energy* 162, 534–541.
- Ferreiro, N., Soto, M., 2003. Anaerobic hydrolysis of primary sludge: influence of sludge concentration and temperature. *Water Sci. Technol.* 47 (12), 239–246.
- Gonzalez, A., Hendriks, A., van Lier, J.B., de Kreuk, M., 2018. Pre-treatments to enhance the biodegradability of waste activated sludge: elucidating the rate limiting step. *Biotechnol. Adv.* 36 (5), 1433–1469.
- Guo, Z.C., Zhou, A.J., Yang, C.X., Liang, B., Sangeetha, T., He, Z.W., Wang, L., Cai, W.W., Wang, A.J., Liu, W.Z., 2016. Enhanced short chain fatty acids production from waste activated sludge conditioning with typical agricultural residues: carbon source composition regulates community functions. *Biotechnol. Biofuels* 9, 1–14.
- Higgins, M.J., Beightol, S., Mandahar, U., Suzuki, R., Xiao, S., Lu, H.W., Le, T., Mah, J., Pathak, B., DeClippeleir, H., Novak, J.T., Al-Omari, A., Murthy, S.N., 2017. Pretreatment of a primary and secondary sludge blend at different thermal hydrolysis temperatures: impacts on anaerobic digestion, dewatering and filtrate characteristics. *Water Res.* 122, 557–569.
- Hong, C., Haiyun, W., 2010. Optimization of volatile fatty acid production with co-substrate of food wastes and dewatered excess sludge using response surface methodology. *Bioresour. Technol.* 101 (14), 5487–5493.
- Huang, J., Zhou, R., Chen, J., Han, W., Chen, Y., Wen, Y., Tang, J., 2016. Volatile fatty acids produced by co-fermentation of waste activated sludge and henna plant biomass. *Bioresour. Technol.* 211, 80–86.
- Kim, M., Yang, Y., Morikawa-Sakura, M.S., Wang, Q., Lee, M.V., Lee, D.-Y., Feng, C., Zhou, Y., Zhang, Z., 2012. Hydrogen production by anaerobic co-digestion of rice straw and sewage sludge. *Int. J. Hydrogen Energy* 37 (4), 3142–3149.
- Lee, W.S., Chua, A.S.M., Yeoh, H.K., Ngoh, G.C., 2014. A review of the production and applications of waste-derived volatile fatty acids. *Chem. Eng. J.* 235, 83–99.
- Li, Y., Park, S.Y., Zhu, J., 2011. Solid-state anaerobic digestion for methane production from organic waste. *Renew. Sustain. Energy Rev.* 15 (1), 821–826.
- Li, J.Q., Liu, W.Z., Cai, W.W., Wang, B., Fidelis, O.A., Zhang, Z.J., Tian, X.D., Wang, A.J., 2019. Applying rhamnolipid to enhance hydrolysis and acidification of waste activated sludge: retarded methanogenic community evolution and methane production. *RSC Adv.* 9, 2034–2041.
- Lin, Y., Ge, X., Liu, Z., Li, Y., 2015. Integration of Shiitake cultivation and solid-state anaerobic digestion for utilization of woody biomass. *Bioresour. Technol.* 182, 128–135.
- Liu, H.B., Xiao, H., Yin, B., Zu, Y.P., Liu, H., Fu, B., Ma, H.J., 2016. Enhanced volatile fatty acid production by a modified biological pretreatment in anaerobic fermentation of waste activated sludge. *Chem. Eng. J.* 284, 194–201.
- Ma, H., Liu, H., Zhang, L., Yang, M., Fu, B., Liu, H., 2017. Novel insight into the relationship between organic substrate composition and volatile fatty acids distribution in acidogenic co-fermentation. *Biotechnol. Biofuels* 10 (1).
- Mata-Alvarez, J., Dosta, J., Romero-Güiza, M.S., Fonoll, X., Peces, M., Astals, S., 2014. A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renew. Sustain. Energy Rev.* 36 (0), 412–427.
- Mould, F., Orskov, E., Mann, S., 1983. Associative effects of mixed feeds. I. Effects of type and level of supplementation and the influence of the rumen fluid pH on cellulolysis in vivo and dry matter digestion of various roughages. *Anim. Feed Sci. Technol.* 10 (1), 15–30.
- Nagase, M., Matsuo, T., 1982. Interactions between amino-acid-degrading bacteria and methanogenic bacteria in anaerobic digestion. *Biotechnol. Bioeng.* 24 (10), 2227–2239.
- Rughonundun, H., Mohee, R., Holtzappple, M.T., 2012. Influence of carbon-to-nitrogen ratio on the mixed-acid fermentation of wastewater sludge and pretreated bagasse. *Bioresour. Technol.* 112, 91–97.
- Russell, J.B., Wilson, D.B., 1996. Why are ruminal cellulolytic bacteria unable to digest cellulose at low pH? *J. Dairy Sci.* 79 (8), 1503–1509.
- Shi, X.S., Yuan, X.Z., Wang, Y.P., Zeng, S.Z., Qiu, Y.L., 2014. Modeling of the methane production and pH value during the anaerobic co-digestion of dairy manure and spent mushroom substrate. *Chem. Eng. J.* 244, 258–263.
- Shirkavand, E., Baroutian, S., Gapes, D.J., Young, B.R., 2017. Pretreatment of radiata pine using two white rot fungal strains *Stereum hirsutum* and *Trametes versicolor*. *Energy Convers. Manag.* 142, 13–19.
- Tan, R., Miyana, K., Uy, D., Tanji, Y., 2012. Effect of heat-alkaline treatment as a pretreatment method on volatile fatty acid production and protein degradation in excess sludge, pure proteins and pure cultures. *Bioresour. Technol.* 118, 390–398.
- Van Lier, J.B., Mahmoud, N., Zeeman, G., 2008. Anaerobic Wastewater Treatment. Biological Wastewater Treatment, Principles, Modelling and Design. pp. 415–456.
- Vavilin, V.A., Fernandez, B., Palatsi, J., Flotats, X., 2008. Hydrolysis kinetics in anaerobic degradation of particulate organic material: an overview. *Waste Manag.* 28 (6), 939–951.
- Wang, Siqu, Zhang, Guangming, Zhang, Panyue, Ma, Xiaowen, Fan, Li, Zhang, Haibo, Xue, Tao, Ye, Junpei, 2018. Mohammad Nabi. Rumen fluid fermentation for enhancement of hydrolysis and acidification of grass clipping. *J. Environ. Manag.* 220, 142–148.
- Wu, Q.L., Guo, W.Q., Zheng, H.S., Luo, H.C., Feng, X.C., Yin, R.L., Ren, N.Q., 2016. Enhancement of volatile fatty acid production by co-fermentation of food waste and excess sludge without pH control: the mechanism and microbial community analyses. *Bioresour. Technol.* 216, 653–660.
- Yin, B., Liu, H.B., Wang, Y.Y., Bai, J., Liu, H., Fu, B., 2016. Improving volatile fatty acids production by exploiting the residual substrates in post-fermented sludge: protease catalysis of refractory protein. *Bioresour. Technol.* 203, 124–131.
- Yuan, Q., Sparling, R., Oleszkiewicz, J.A., 2011. VFA generation from waste activated sludge: effect of temperature and mixing. *Chemosphere* 82 (4), 603–607.
- Zahmatkesh, M., Spanjers, H., van Lier, J.B., 2018. A novel approach for application of white rot fungi in wastewater treatment under non-sterile conditions: immobilization of fungi on sorghum. *Environ. Technol.* 39 (16), 2030–2040.
- Zhang, C.S., Su, H.J., Baeyens, J., Tan, T.W., 2014. Reviewing the anaerobic digestion of food waste for biogas production. *Renew. Sustain. Energy Rev.* 38, 383–392.
- Zhang, D., Fu, X., Jia, S., Dai, L., Wu, B., Dai, X., 2016. Excess sludge and herbaceous plant co-digestion for volatile fatty acids generation improved by protein and cellulose conversion enhancement. *Environ. Sci. Pollut. Res. Int.* 23 (2), 1492–1504.
- Zhou, A., Guo, Z., Yang, C., Kong, F., Liu, W., Wang, A., 2013. Volatile fatty acids productivity by anaerobic co-digesting waste activated sludge and corn straw: effect of feedstock proportion. *J. Biotechnol.* 168 (2), 234–239.
- Zhou, A.J., Du, J.W., Varrone, C., Wang, Y.Z., Wang, A.J., Liu, W.Z., 2014. VFAs bio-production from waste activated sludge by coupling pretreatments with *Agaricus bisporus* substrates conditioning. *Process Biochem.* 49 (2), 283–289.