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Occurrence, distribution, and potential influencing factors of sewage sludge components derived from nine full-scale wastewater treatment plants of Beijing, China

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ABSTRACT

Millions of tons of waste activated sludge (WAS) produced from biological wastewater treatment processes cause severe adverse environmental consequences. A better understanding of WAS composition is thus very critical for sustainable sludge management. In this work, the occurrence and distribution of several fundamental sludge constituents were explored in WAS samples from nine full-scale wastewater treatment plants (WWTPs) of Beijing, China. Among all the components investigated, active heterotrophic biomass was dominant in the samples (up to 9478 mg/L), followed by endogenous residues (6736 mg/L), extracellular polymeric substances (2088 mg/L), and intracellular storage products (464 mg/L) among others. Moreover, significant differences ($p < 0.05$) were observed in composition profiles of sludge samples among the studied WWTPs. To identify the potential parameters affecting the variable fractions of sludge components, wastewater source as well as design and operational parameters of WWTPs were studied using statistical methods. The findings indicated that the component fraction of sewage sludge depends more on wastewater treatment alternatives than on wastewater characteristics among other parameters. A principal component analysis was conducted, which further indicated that there was a greater proportion of residual inert biomass in the sludge produced by the combined system of the conventional anaerobic/anoxic/oxic process and a membrane bioreactor. Additionally, a much longer solids retention time was also found to influence the sludge composition and induce an increase in both endogenous inert residues and extracellular polymeric substances in the sludge.

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Introduction

Biological approaches have been extensively used in wastewater treatment plants (WWTPs) worldwide. However, substantial amounts of waste activated sludge (WAS) are generated annually from WWTPs with a marked growth rate (Kroiss, 2004). As estimated, about 8.2 and 3.6 million tons of WAS has been produced in 2009 in the United States and China, respectively (Jiang et al., 2009). Without appropriate disposal at a landfill or direct incineration, this biomass residue will lead to severe environmental and social burdens. Moreover, given the global concerns with respect to energy conservation and resource scarcity in this century, there is increasing awareness that municipal wastes such as WAS should be considered as a valuable resource from which organics, nitrogen, and phosphorus can be harvested to produce energy and raw materials (Wang et al., 2012).

Even if matter is disposed of as a pollutant or recycled as a beneficial resource, sustainable management of WAS still requires more reliable information on the sludge composition because WAS contains a variety of constituents. Furthermore, WAS shows unpredictable sludge characteristics and its component proportion varies with different temporal and spatial contexts, which can have a significant impact on the performance of downstream WAS applications (Jiang et al., 2011; Li et al., 2008; Yin et al., 2013). Additionally, numerous technical issues in handling and disposing WAS arise because of a lack of in-depth understanding of the composition of WAS (Chen et al., 2011; Dursun et al., 2004; Feng et al., 2009). Therefore, it is essential to investigate the composition of WAS derived from numerous WAS samples that account for temporal and geographical factors.

In addition, WAS samples from different WWTPs exhibit varying characteristics and are as unique as fingerprints. At present, numerous alternative combinations of anaerobic/anoxic/oxic units have been applied in urban wastewater service to prevent aquatic ecosystems and human health from

severe contaminations (Cassidy and Belia, 2005; Kang et al., 2011; Liu et al., 2010; Zeng et al., 2010). Nevertheless, little research was made on comparing WAS compositions among different wastewater treatment alternatives, and on determining the potential reasons that lead to significant differences among WAS samples by analyzing the influencing factors in the design and operation of different WWTPs.

We thus explored the concentrations and composition profiles of several essential constituents (active microorganisms, residual inert biomass, internal storage products, and extracellular polymeric substances) in the sludge samples collected from nine full-scale municipal WWTPs of Beijing, China. The potential parameters influencing dynamic component fractions in WAS were subsequently demonstrated by applying several statistical analysis techniques. Overall, the present work provides beneficial information on origin-specific WAS characteristics, which would be significantly beneficial to decision-makers for pursuing sustainable management of WAS.

1. Materials and methods

1.1. Samples collection

The sampling map and sites are shown in Fig. 1. All the sludge samples were collected from secondary clarifiers and sealed in different plastic containers, which were freeze-dried immediately, and were then stored at 4°C before further analysis. Details of the nine WWTPs are represented in Table 1; these include the service population, treatment capacity, treatment technique, and influent characteristics. It should be noted that even though only nine full-scale WWTPs were included in this work, 11 different biological wastewater treatment alternatives were covered under the investigation as some WWTPs were equipped with two parallel water treatment lines (such as No. 1 WWTP).

1.2. Assumption and determination of sludge components

Theoretically, the activated sludge generated from biological wastewater treatment processes consists of four conceptual components (McKinney, 1974): active microbial mass, endogenous mass, inner organic mass, and inert inorganic mass. However, in practice, it is difficult to search appropriate analytical techniques to carry out direct quantifications of these sludge substances without making reasonable assumptions. In the literature (Ni et al., 2009), the measurable activated sludge can be expressed by mixed liquid volatile suspended solid (MLVSS) in milligrams of chemical oxygen demand (COD) per liter and is calculated from Eq. (1):

$$\text{MLVSS} = X_H + X_I + X_{\text{EPS}} + X_{\text{STO}} \quad (1)$$

where the symbols for concentrations of sludge components are denoted as active heterotrophic biomass (X_H), internal storage products (X_{STO}), residual inert biomass (X_I), and extracellular polymeric substances (EPS, X_{EPS}). Thus, these substances (X_H , X_I , X_{EPS} , and X_{STO}) are employed as representative sludge components for further analysis throughout this work.

Fig. 1 – Sampling locations of the investigated sludge samples in Beijing, China.

Table 1 – Detailed information of the investigated wastewater treatment plants (WWTPs).

WWTPs	Capacity (10 ⁴ /(m ³ ·day))	Population (10 ⁴ capita/day)	Sewage source	Influent COD (mg/L)	Treatment techniques *	SRT (day)
No. 1	3.5	15	Domestic 85%, industrial 15%	625.6	OD ₍₁₎	11–13
No. 1	3.5	15	Domestic 85%, industrial 15%	625.6	A ² /O + MBR	23–27
No. 2	20	48	Domestic 70%, industrial 30%	404.9	OD ₍₂₎	11–14
No. 3	8	30	Domestic 85%, industrial 15%	449.7	OD ₍₃₎	11–13
No. 4	5	26	Domestic 20%, industrial 80%	533.5	CASS ₍₁₎	14–16
No. 5	5	23	Domestic 20%, industrial 80%	225.4	CASS ₍₂₎	14–16
No. 6	5	20	Domestic 70%, industrial 30%	573.5	CASS ₍₃₎	14–16
No. 7	20	40.7	Domestic 85%, industrial 15%	531.2	Inverted A ² /O	8–10
No. 7	20	40.7	Domestic 85%, industrial 15%	531.2	A ² /O ₍₁₎	13–15
No. 8	60	206	Domestic 85%, industrial 15%	543.5	A ² /O ₍₂₎	11–12
No. 9	100	15	Domestic 50%, industrial 50%	410.0	CAS	13–17

SRT: Solids retention time; WWTPs: wastewater treatment plants; COD: chemical oxygen demand; SRT: solids retention time; OD: oxidation ditch; A²/O + MBR: combination of typical A²/O process and membrane bioreactor; CASS: cyclic activated sludge system; CAS: conventional activated sludge; A²/O: conventional anaerobic/anoxic/oxic process; inverted A²/O: inverted anaerobic/anoxic/oxic.

* Subscripts represent the alternative transformations of the treatment technique.

Subsequently, the determinations of COD and MLVSS were carried out following Standard Methods (APHA, 1995), whereas a batch approach was used to quantify the concentration of X_H (Kappeler and Gujer, 1992). The EPS of the sludge samples were extracted using the NaOH method, as described in a previous study (Liu and Fang, 2002). As the main components of EPS, the measurements of the soluble protein and polysaccharides used typical approaches (Dubois et al., 1956; Frolund et al., 1995); the sum of soluble protein and polysaccharides was then used to represent EPS. For extraction (Pratt et al., 2004) and determination (Ni et al., 2010) of X_{STO} , samples of 10 mL were centrifuged at 4000 r/min for 10 min and decanted, and the biomass pellet was freeze-dried at 54°C to remove the moisture content. The solid material was suspended in 2 mL of acidic methanol solution (3% H₂SO₄) and 2 mL of chloroform. The glass tube was screwed tightly and heated to 100°C for 6 hr. After cooling, 1 mL of Milli-Q water was added to the tube and the resultant mixture was shaken vigorously for 10 min. When the phases were separated, 1 mL of the bottom organic layer was removed to the gas chromatography (GC) vials for X_{STO} determination. After the GC analysis, X_{STO} measured in this work was proven mainly to be poly-hydroxybutyrate. The concentration of X_I was assumed to be the difference between MLVSS and the sum of X_H , X_{EPS} , and X_{STO} (Ni et al., 2009).

1.3. Statistical analysis techniques

Herein, statistical analyses were conducted by using the statistical software SPSS 19.0. Spearman correlation analysis (Shin et al., 2011) was employed to evaluate the correlations among the focused constituents in sludge samples. Comparisons of constituent proportions were performed utilizing the two-sample Kolmogorov–Smirnov nonparametric test (Qin and Zhang, 1997). For all comparisons in this work, $p < 0.05$ was considered significant. In addition, principal component analysis (PCA) on the analytical data was executed to attain a visual illustration of the main characteristics and the principal components (PCs) for eigenvalues greater than 1 (Scholkopf et al., 1998).

2. Results and discussion

2.1. Concentrations and component proportions of the WAS samples

Initially, the concentration levels of the individual sludge components of the sludge samples were presented by box-and-whisker plots, as shown in Fig. 2. Specifically, the concentrations of X_H , X_I , X_{EPS} , and X_{STO} in the WAS samples were in the range of 558.8–9478.0 mg/L (mean: 3497.0 mg/L),

Fig. 2 – Box-and-whisker plots of the four investigated components in sludge samples collected from nine WWTPs in Beijing. The horizontal black line in the box represents the median value, and the lower and upper edges of the box mark the 25th and 75th percentiles. The whiskers extending from the box show the highest and lowest values. The singular values are represented by the cycle symbol, which were beyond the 150th percentile of the difference between 25th and 75th percentiles.

Table 2 – Spearman's rank correlations among X_H , X_I , X_{EPS} , and X_{STO} in the WAS samples.

	X_H	X_I	X_{EPS}	X_{STO}
X_H	1			
X_I	0.270	1		
X_{EPS}	0.554**	0.390	1	
X_{STO}	0.435*	0.658**	0.639**	1

WAS: waste activated sludge.
 ** Correlation is significant at the 0.01 level (2-tailed).
 * Correlation is significant at the 0.05 level (2-tailed).

200.6–6736.0 mg/L (mean: 3239.6 mg/L), 244.4–2088.0 mg/L (mean: 980.9 mg/L), and 0–464.0 mg/L (mean: 175.9 mg/L), respectively. In addition, Spearman's correlation analysis, as represented in Table 2, showed significant correlations ($p < 0.05$) among the constituents (expect X_H and X_I , as well as X_{EPS} and X_I), which suggested common sources and similar environmental fates of sludge components generated from the WWTPs in this study. The component proportion profiles of X_H , X_I , X_{EPS} , and X_{STO} in the samples derived from 11 different biological wastewater treatment alternatives are presented in Fig. 3. The proportions of the four sludge components were found to vary significantly with various sewage sources and districts of the alternative wastewater treatment processes ($p < 0.05$).

To further evaluate the potential factors influencing the component proportions in WAS, related information, such as wastewater sources (domestic, industrial, or combined), as well as design parameters and operation conditions of the WWTPs (i.e., treatment capacity, service population, and wastewater treatment alternative) were investigated, and are discussed in subsequent sections.

2.2. Factors causing variable component proportions in WAS samples

2.2.1. Treatment capacity and service population

Serving as a significant precursor to the design and operation of WWTPs, treatment capacity and service population were investigated to evaluate the components of WAS. Specifically, the Spearman's correlation analysis showed that the proportions of the investigated components in the sludge samples have no significant relationship with individual parameters ($p > 0.05$).

2.2.2. Sewage source

Generally, municipal sewage and industrial wastewater were the essential sources of WWTPs. The WWTPs investigated in this work were all fed with a combination of municipal sewage and industrial wastewater. Among them, seven WWTPs were driven with 70%–85% of domestic sewage, and the remaining WWTPs were fed with >50% of industrial wastewater (Table 1). As represented in Fig. 3, the top two highest active heterotrophic biomass (X_H) fractions (77.3% and 57.7%, respectively) in the samples were detected in WWTP nos. 1 and 8 (i.e., OD₍₁₎ and A²/O₍₂₎ respectively), which were both fed with a greater fraction (85%) of domestic wastewater. Since the industrial wastewater investigated herein was mainly derived from electronics factories and thus contained a variety of toxic substances, it was evident that a lower fraction of industrial waste streams would enhance the probability of preventing active microorganisms from chemical toxicity. Further, the proportion of EPS detected in WWTPs fed with a larger fraction of domestic sewage was also much higher than those in WWTPs driven with greater industrial waste streams. Thus, the proportions of microorganism-related substances in sludge probably associated with the different sources of the sewage in the explored WWTPs.

Fig. 3 – Statistical proportions of the four investigated components in sludge samples derived from 11 different biological wastewater treatment alternatives.

Fig. 4 – The loading (a) and score (b) plots of PCA by the database of the four investigated constituents in the WAS samples. PCA: principal component analysis.

2.2.3. Biological wastewater treatment alternative

To date, numerous biological wastewater treatment alternatives have been applied extensively worldwide owing to their reasonable operating and maintenance costs. Nevertheless, there have been few studies showing the component proportions of X_H , X_I , X_{EPS} , and X_{STO} in WAS as relevant to the type of biological wastewater treatment technique. Table 1 summarizes the 11 different biological wastewater treatment alternatives of the nine full-scale WWTPs investigated. These were mainly divided into conventional activated sludge (CAS) process, cyclic activated sludge system (CASS), oxidation ditch (OD), conventional anaerobic/anoxic/oxic (A^2/O) process, inverted anaerobic/anoxic/oxic (inverted A^2/O), and a combination of typical A^2/O process and membrane bioreactor ($A^2/O + MBR$). In the present work, the relation between treatment techniques and the proportions of sludge constituents was studied using a PCA approach.

The varimax rotation in the present work reduced the four variables to two PCs with eigenvalues greater than 1, which represent 82.12% of the cumulative variances. Fig. 4 portrays the loading and score plots of the two PCs. As represented in Fig. 4a, PC1 accounted for 51.48% of the total variance and illustrates strong positive loadings on residual inert biomass (X_I), whereas PC2 accounted for as much as 30.64% of the total variance and shows moderately positive loadings for the extracellular polymeric substances (X_{EPS}). Furthermore, the score plots of PCA in Fig. 4b were grouped by wastewater treatment alternatives to visualize their potential connections. The average loading scores of PC1 and PC2 in the sludge samples collected from the WWTPs were respectively in the order of “ $A^2/O + MBR > Inverted A^2/O > CAS > CASS > OD > A^2/O$ ” and “ $CAS > Inverted A^2/O > A^2/O + MBR > CASS > A^2/O > OD$ ”. This result indicates that the fractions of sludge constituents could vary significantly based on the wastewater treatment alternatives. For example, the PCA outcomes illustrate that $A^2/O + MBR$ has markedly the highest loading scores of PC1 in the component plot (Fig. 4b), suggesting a greater proportion of residual inert biomass in the sludge produced by the $A^2/O + MBR$ plant. Biological wastewater treatment takes one of the two general forms: suspended growth systems (e.g., CAS, CASS, OD, and A^2/O) or attached growth systems (e.g., trickling filters). Depending on the operational conditions, both could function differently. For example, the

critical operational variable for suspended growth system is the solids retention time (SRT), and a longer SRT is able to strengthen endogenous metabolisms, which thereby lead to increased residual inert substances in sludge (Huang et al., 2001; Ouyang and Liu, 2009; Teck et al., 2009). Thus, it could be understandable that a greater fraction of residual inert biomass was presented in the $A^2/O + MBR$ sludge, since MBRs are similar to suspended growth systems that use sedimentation for biomass separation, but can be operated at a much higher SRT (Yang et al., 2006). In the subsequent analysis, $OD_{(1)}$ and $A^2/O + MBR$ systems which operated with very different SRTs (11–13 days and 23–27 days, respectively) in spite of feeding with same influent wastewater (WWTP no. 1), exhibited markedly different fractions of nonbiodegradable endogenous residues in their sludge (see PC1 of Fig. 4b), and a greater fraction of residues was represented in the sludge of the latter system. In this regard, it was evident that a longer SRT can affect and improve the levels of residual inert substances in sludge.

On the other hand, the EPS content in sludge was also found to be relevant with respect to the biological treatment techniques (PC2 of Fig. 4b). Literature on the effect of operational parameters such as SRT on EPS generation is conflicting. A few studies have reported higher EPS concentrations at longer SRTs (Badireddy et al., 2010; Ng and Hermanowicz, 2005), whereas others have observed lower concentrations at longer SRTs (Ahmed et al., 2007; Masse et al., 2006). In additional literature the EPS content was found to be independent of the SRT (Sponza, 2002). In the present study, it was found that the SRT would affect the EPS proportion in sludge, which was derived from the comparison of the $A^2/O_{(1)}$ and inverted A^2/O processes in WWTP no. 7 (Fig. 4b, PC2), suggesting that a longer SRT induced an increase in the EPS fraction in sludge. Actually, the EPS fraction is growth-related, and is determined by a dynamic balance between microbial production and subsequent degradation (Faust et al., 2014). At short SRTs, the microbial activity is strong in the bioreactor, and much EPS could be produced by microbes under substrate utilization, whereas at long SRTs, microbes are in the endogenous respiration or decline period and proteins are released from the microorganisms into the network structure of EPS.

Overall, the fractions of residual inert substances and EPS in sludge were found to be relevant with biological wastewater treatment processes, and were significantly impacted by operational variables such as SRT. However, further comparative studies with a wider coverage of treatment approaches including suspended and attached growth systems are essential to decipher the further relationship between biological treatment methods and sludge composition. Additionally, elaborate explorations on a plant are needed to verify whether considerable variations really occur in the inert residues and EPS collected from the same system but sampled at different SRTs.

3. Conclusions

In this, a total of four essential components including active heterotrophic biomass, internal storage products, residual biomass, and extracellular polymeric substances in WAS samples were collected from nine domestic WWTPs which includes 11 alternative activated sludge processes in Beijing, China. The sludge samples obtained from the different WWTPs showed variable concentrations and composition profiles of the studied sludge components, highlighting the significance of exploring factors that cause such significant differences. The results of several statistical analysis techniques revealed that the fraction level of the sludge constituents was associated with the composition of sewage source, and particularly the treatment techniques of the studied WWTPs. Furthermore, SRT was found to be an important parameter as it was able to influence the levels of inert residues and EPS in sludge, and a longer SRT could induce increases in unbiodegradable endogenous residues and EPS contents in sludge.

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