

The bottlenecks and causes, and potential solutions for municipal sewage treatment in China

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Abstract

Since about the 1990s China has achieved remarkable progress in urban sanitation. The country has built very extensive infrastructure for wastewater treatment, with 94.5% treatment coverage in urban areas and legally mandated nation-wide full nutrient removal implemented. However, municipal wastewater treatment plants (WWTPs) in China are still confronted with issues rooted in the unique sewage characteristics. This study compares energy recovery, cost of nutrient removal and sludge production between Chinese municipal WWTPs and those in countries with longer wastewater treatment traditions, and highlights the cause-effect relationships between Chinese sewage characteristics – high inorganic suspended solids (ISS) loads, and low COD and C/N ratio, and municipal WWTP process performance in China. Integrated design and operation guidelines for municipal WWTPs are imperative in relation to the unique sewage characteristics in China. Cost-effective measures and solutions are proposed in the paper, and the potential benefits of improving the sustainability of municipal WWTPs in China are estimated.

Key words: energy recovery, municipal wastewater treatment, nutrient removal, sludge production, sustainability, wastewater treatment in China

INTRODUCTION

China has achieved remarkable progress in urban sanitation since about the 1990s. Annual municipal sewage treatment capacity reached $49.2 \times 10^9 \text{ m}^3$, with 94.5% treatment coverage in urban areas in 2017 (CUWA 2018). Nutrient (nitrogen and phosphorus) removal is required legally and has been implemented at national scale. However, little energy recovery is practised, nutrient removal is expensive, and sludge production is high at municipal wastewater treatment plants (WWTPs). The unique characteristics of Chinese sewage/wastewater are the principal cause of the low efficiency of municipal WWTPs (Cao & Daigger 2018). Sewer leakage is the prime determining factor leading to China's unique sewage characteristics (Cao *et al.* 2019). Recently, three Chinese ministries promulgated a document entitled *Three Years Action Plan for Increasing the Quality and Efficiency of Urban and Town Wastewater Treatment* (MOC 2019) emphasizing the key role of sewer rehabilitation in urban sanitation and ecology, and indicating a turning point in Chinese urban sanitation strategy. Given the heavy tasks involved, and the huge investment and long times needed for sewer rehabilitation, cost-effective and quick actions and measures are necessary to improve the sustainability of Chinese municipal sewage treatment. This study has three objectives: i. to compare energy recovery, nutrient removal and sludge production at municipal WWTPs in China with those in other countries

with longer wastewater treatment traditions; ii. to reveal the cause-effect relationships between Chinese sewage characteristics and the process performance of municipal WWTPs; and iii. to propose cost-effective measures and solutions to increase the sustainability of municipal WWTPs.

METHODOLOGY

Energy recovery in China is based on comparisons of WWTPs using anaerobic digestion (AD), and combined heat and power (CHP) in China, and Europe, USA and Singapore. As primary settling tanks and AD are used seldom in China, sludge production is mainly based on observed biomass yield coefficients, and influent ISS accumulation in the process is calculated on the basis of mass balance (Grady *et al.* 1999).

RESULTS AND DISCUSSION

Municipal wastewater treatment – sustainability

Table 1 shows that less than 5% of Chinese municipal WWTPs use AD (Dai 2017), which is very low compared to Europe, USA and Singapore. This indicates limited energy recovery from internal sources through AD and/or CHP in China, although the technology has been available in the countries with longer wastewater treatment traditions (Kroiss & Cao 2014). Failure to use AD leads not only to sludge stabilization issues (Dai 2017; Hu 2019; Wang 2019b), but also increased sludge production (lack of VSS destruction in AD or lime, etc, addition for stabilization) and hygiene problems, along with sludge disposal and reuse difficulties (Dai 2017; Hu 2019).

In order to meet strict nutrient discharge standards (such as China first grade class A discharge standards for municipal WWTPs, TN (total nitrogen) <15 mg-N/L, first and TP (total phosphorus) <0.5 mg-P/L, and TN <10 mg-N/L, TP <0.3 mg/L implemented in sensitive areas in several provinces) carbon dosing (and chemicals for phosphorus removal) is practiced in many WWTPs in China (Zheng 2017) despite the limited use of primary settling (PS) tanks. Fundamentally, this is due to the low C/N ratio of the incoming sewage since, for more typical sewage, conventional biological nitrogen removal processes can achieve effluent TN <10 mg-N/L with few carbon additions (Wang 2019b). Because of chemical use, chemicals comprise the second highest operating cost (after power) in some plants (Qian 2018). Chemical costs are expected to increase further, if stricter nutrient discharge standards (e.g. TN <5 mg-N/L and TP <0.1 mg-P/L) are imposed. This will impose further economic burdens on plant operations and local authorities, apart from which increased chemical addition is unsustainable when the primary energy used and corresponding greenhouse gas emissions are considered (van Loosdrecht *et al.* 2014).

Wastewater treatment sludge consists of excess biomass, refractory particulate COD and mineral particles (ISS). Sludge production is governed by the wastewater characteristics, process and site environment. Table 2 presents the annual average sludge production (dry solids (DS) based) related to COD removal in wastewater treatment in China in 2015, 2016 and 2017 (CUWA 2016, 2017, 2018). The three-year average is 0.69 kg/kg-COD removed. Given the limited use of PS 10–20%

Table 1 | Proportion of municipal WWTPs with AD in China and other countries (%)

China ^a	Denmark	France ^b	Germany	Netherlands	Singapore ^c	Sweden	Switzerland	UK	USA
<5	52	39	87	66	100	56	95	97	68

The otherwise: Wang (2019b).

^aDai (2017).

^bYang & Donnaz (2017).

^cCao *et al.* (2014).

Table 2 | Chinese annual COD removal and sludge production and sludge observed yield coefficients for 2015, 2016 and 2017

	2015	2016	2017
COD removed	2.47 (kg × 10 ⁻¹) ^a	13.00 (kg × 10 ⁹) ^b	13.77 (kg × 10 ⁹) ^c
Sludge production (DS)	1.70 (kg × 10 ⁻¹) ^d	8.00 (kg × 10 ⁹) ^e	10.53 (kg × 10 ⁹) ^f
Sludge production/COD removed, Kg sludge/kg COD removed	0.69	0.62	0.77

^aCOD removed, kg × 10⁻¹/m³, average of municipal WWTPs (CUWA 2016).^bCOD removed, kg × 10⁹, all municipal WWTPs, (CUWA 2017).^cCOD removed, kg × 10⁹, all WWTPs (CUWA 2018).^dSludge produced (DS), kg × 10⁻¹/m³, average of municipal WWTPs (CUWA 2016).^eSludge produced (DS), kg × 10⁹, all municipal WWTPs (CUWA 2017).^fSludge produced (DS) kg × 10⁹, all municipal WWTPs (CUWA 2018).

(Zheng 2017; Wang 2019c) and AD (<5%, Dai 2017), the sludge production per kg/COD removed can be regarded as the observed sludge yield (coefficient) from the activated sludge process (Grady *et al.* 1999). The sludge production yield based on the sewage composition in China in 2017 (Cao *et al.* 2019), assuming an influent VSS/TSS ratio of 80% (Henze *et al.* 2002) and prevailing biological nutrient removal process, is calculated according to Paul *et al.* (2001). For biological nitrogen and phosphorus (BNPR) and chemical phosphorus removal (molar Fe/P removal ratio of 1.5, 80% of P removed) (hybrid) process with influent RBCOD (readily biodegradable COD)/COD ratio of 8%, BOD/P 18%, VSS/TSS 80% and sludge retention time (SRT) 18 days, the sludge yield (DS) should be 0.48 kg/kg COD removed. This includes 30% more sludge than conventional biological nitrogen removal (BNR) (3.7 kg/kg COD removed) due to metal dosing for chemical P removal. The actual 0.69 kg/kg COD removed is 44% higher than the 0.48 kg/kg COD removed with the normal (80%) influent VSS/TSS ratio.

Investigations of sludge production in WWTPs in China have shown that WWTPs generally yield approximately 0.48 kg-DS/kg COD removed when the influent characteristics are more or less normal, while those with sludge yields of 0.69 or higher are treating sewage with abnormal characteristics. It is possible that the high yield observed is due to extra mineral accumulation originating from the influent wastewater. Average sludge yield in France, where 39% of WWTPs have AD, is 0.44 kg-/kg COD removed (calculated from 0.97 kg-/kg-BOD₅elim assuming 1 mg BOD₅ = 2.2 mg COD) (Yang & Donnaz 2017). An even lower sludge production coefficient 0.24 kg-DS/kg COD removed, only one third that in China, was reported in Singapore where all municipal WWTPs apply AD for energy recovery plus solids reduction of around 35% (Cao *et al.* 2014). These sludge production coefficients are quoted for illustration, given the sewage characteristics and process differences in France and Singapore. They demonstrate, however, that current Chinese sludge production coefficients are truly relatively high.

Causes of low efficiency performance: unique sewage characteristics

Wastewater characteristics are critical in designing and modelling activated sludge processes (Henze *et al.* 2002; Henze & Comeau 2008). An earlier study (Cao *et al.* 2019) quantified the sewer system leakage fractions in four cases, and demonstrated that sewer leakage leads to three sewage characteristics; that is, high ISS and low COD and C/N ratio, in China.

Investigation has shown that the influent VSS/TSS ratio of the WWTPs in some areas with reasonably well-managed sewer systems in China is between 50 and 60%. This is below the 60–80% median range (Henze & Comeau 2008; Van Haandel & van der Lubbe 2012), although more data are required for a national picture. The low influent ratios reported – COD/SS <1 and BOD₅/SS = 0.3–0.5 in China (Dai 2017; Ji 2017; Wu 2017; Yang 2017; Zheng 2017) are also indicators of high ISS loads (sand, etc.) in the sewage. The influent ISS/TSS fraction has a direct impact on the mixed liquor inorganic suspended solids concentration (MLISS) as shown by Equation (1)

(Grady *et al.* 1999) assuming no PS:

$$\text{MLISS} = \text{ISS}_{\text{IO}} \times (\Theta_c / \tau) \quad (1)$$

where, ISS_{IO} : influent ISS, Θ_c : sludge retention time SRT; τ : hydraulic retention time.

Using Equation (1) for an activated sludge process without PS, with 12-day SRT and 0.5-day HRT, and influent VSS of 180 mg/l, ISS 79 mg/L (VSS ratio of 70% (180/(79 + 180))), a 10% VSS ratio reduction (ISS increased to 120 mg/l) yields a mixed liquor increase to approximately 1,000 mg-ISS/L, demonstrating the sensitivity of ISS to the VSS fraction. Modelling showed that a 10% decrease in the influent ISS/TSS (increasing VSS/TSS) ratio can cause a 15–25% increase in the MLVSS fraction (Cao & Daigger 2019). That fraction (and AD wet feed) in most WWTPs in China is between 30 and 60%. The lower MLVSS fractions are often from WWTPs with high influent ISS from poorly managed sewer systems, while relatively higher fractions are often from WWTPs with lower influent ISS, generally from properly managed systems or in northern China, where ex-filtration occurs (Fan *et al.* 2015; Dai 2017; Ji 2017; Zheng 2017). The average volatile solids fraction reported in China is below 50% (Wang 2019b), well below the normal 70–75% range (Henze *et al.* 2002). This indicates significant inorganic solids input and accumulation, even considering the accumulation of minerals used to remove phosphorus chemically (volatile solids fraction 60%) (USEPA 1987).

A low MLVSS fraction is detrimental to both activated sludge and AD process performance. Taking a volatile solids fraction of 70% as the comparison basis, the lower fraction of 50% will require a volume increase of approximately 30% for the activated sludge tanks and AD. Alternatively, the activated sludge process SRT will be reduced. This could impact process performance adversely, if the effect of high influent ISS was ignored in the original design, potentially resulting in elevated effluent ammonia in winter.

A low volatile solids fraction in the AD feed reduces the biogas production per unit effective volume (or per unit sludge). This would result in the need for additional volume, or the SRT and total biogas production could be reduced. The combination of reduced biogas yield with solids depositing in AD, and pipe clogging caused by sand and abrasive wear (Jiang 2014; Ji 2017) has resulted in the very low current application of AD in China. Of many factors, the high ISS content of many wastewaters is the main technological obstacle to AD application in China (Jiang 2014; Dai 2017; Ji 2017). This further increases the investment required for solids processing at municipal WWTPs (Hu 2019). High ISS influent concentrations also result in the need for additional capacity for final settling and solids treatment, and energy wastage in solids treatment.

The accumulation of influent ISS in the primary and secondary sludges is responsible for high sludge production (Grady *et al.* 1999). Modelling showed that, when the influent ISS/TSS ratio decreases from 70 to 60%, or from 60 to 50%, sludge production (DS) decreases by approximately 30%, with or without PS (Cao & Daigger 2019). In summary, high influent sewage ISS imposes multiple adverse impacts on municipal WWTP performance and operation.

The influent COD concentration to Chinese municipal WWTPs in 2016 averaged only 267 mg-COD/L (CUWA 2017), almost half that in other countries (Table 3). This is attributed to sewer in-line biodegradation and leakage (Cao *et al.* 2019). The influent suspended solids (SS) concentration for many WWTPs is around 100 mg/L (Cao *et al.* 2019), some 150 mg/L below that of typical sewage elsewhere (Henze *et al.* 2002), and suggesting possible particulate settling and accumulation in sewers (Xu *et al.* 2019).

The low influent COD results in low biomass concentration (MLVSS). Thus, the higher the influent ISS, the higher both the non-volatile solids fraction of the mixed liquor and the sludge production per unit COD removed. This makes achieving high efficiency grit removal very important for downstream process performance when treating dilute influent. Due to the low influent COD, PS has been removed from most (80 to 90%) Chinese WWTPs (Zheng 2017; Wang 2019c) to allow raw sewage,

Table 3 | Influent COD concentrations in Chinese municipal WWTPs and elsewhere (mg-COD/L)

China ^a	France	Germany	Netherlands	Singapore ^b	Sweden	UK
267	592	548	470	565	477	612

Other countries: Pons *et al.* (2004).

^aCUWA (2016).

^bCao *et al.* (2014).

which has a higher C/N ratio, to flow into the biological process. It is noted that low influent COD concentrations do not always point to the abolition of AD – see below – although, compared to higher influent COD, total energy recovery may be affected.

The influent C/N ratio in municipal WWTPs in China is between 5.4 and 10.9 (Sun *et al.* 2016), below the typical range elsewhere of between 8 and 12 (Henze *et al.* 2002). A recent study showed that the influent C/N ratio at several Chinese municipal WWTPs – for example, Beijing, Shanghai and Guangzhou – was between 7.5 (Guangzhou) and 8.8 (Beijing), and averaged 8.0 (Cao *et al.* 2019). This low ratio is due to the high level of in-line COD biodegradation (20–30%) (Cao *et al.* 2019). The low ratio leads to carbon shortages for high efficiency BNR. Given the potential high fraction of inert COD, the efficiency of denitrification and biological phosphorus removal at some Chinese WWTPs could be further reduced, compared to that expected for typical sewage with similar influent C/N ratios, which contain a lower proportion of inert COD (Puig *et al.* 2010).

Nowadays, PS is commonly omitted from sewage treatment processing in China with the aim of improving the carbon supply and thus BNR efficiency. Taking COD removal (30–40%) by PS into account, its omission can result in an increase of up to 40% in the activated sludge tank volume, as well as a significant increase in the secondary settling tank surface area. These lead to increased volumes and hydraulic retention times, increasing construction costs significantly. The improvement in denitrification efficiency due to introducing more readily biodegraded particulate COD, however, depends on the rate of hydrolysis of particulates (Henze & Mladenovski 1991) and temperature. Measurable improvement in denitrification efficiency might thus be achieved in the summer while not occurring in winter; that is, the benefits of omitting PS may not be straightforward. Detailed analysis of the sewage characteristics, including nitrate up-take rate tests (Kristensen *et al.* 1992), and special consideration of flexibility in both process design and operating strategy, are needed.

To meet strict nutrient removal discharge standards (e.g. TN <10 mg N/L), external carbon dosage is practised increasingly commonly. For example, a 100,000 m³/d WWTP needs to spend approximately 3 million Chinese Yuan (about 450,000 USD) annually at current market prices purchasing acetic acid (HAc) (equivalent to 20 mg-HAc/L). Purchasing carbon and chemicals is becoming a heavy burden on plant operation.

Potential solutions

Development of integrated guidelines for the design and operation of municipal WWTPs

In response to China's unique sewage characteristics, guidelines for the design and operation of municipal WWTPs are needed. They should integrate issues of local sewage characteristics, discharge requirements, location, treatment capacity, and energy, chemicals and sludge disposal costs, etc. As a system input, sewage characteristics play essential roles in the selection and design of the biological process. Conventional processes may not be applicable to treat dilute sewage (e.g. around 100 mg-COD/L) in parts of southern China; instead, processes like membrane-based technology or SANI (sulfate reduction, autotrophic denitrification and nitrification) (van Loosdrecht & Chen 2012) should be considered. Denitrification enhancement with biodegradable particulate COD (by omitting PS) may be feasible in warm climates, but not in cold regions.

AD application for energy recovery in Chinese municipal WWTPs should be high on the agenda. In the USA at the turn of the century it was economically feasible to use AD in WWTP with capacities exceeding 100,000 m³/d (Kroiss & Cao 2014). More recently, AD has become economic in even smaller plants with capacities of 20,000–40,000 m³/d. In Europe, they can yield economic benefits at around 10,000 m³/d (50,000 PE) (Kroiss & Cao 2014). The economic feasibility of AD at a Chinese municipal WWTP should be determined in the context of local conditions.

Recommended actions

Given the long time required for sewer rehabilitation and the current state of municipal WWTPs, cost-effective measures and solutions to improve WWTP performance need to be figured out and implemented while integration guidelines are formulated. Potential improvements in grit removal and sludge fermentation, and the application of AD and CHP are described below. Taking the effect of plant size on economic benefits and cost-effectiveness into account, grit removal improvement seems worthwhile for all WWTPs, while sludge fermentation, and the application of AD and CHP for energy recovery, would be suitable for relatively large WWTPs with relatively high influent COD concentrations (e.g. >300 mg/L).

Enhancement of grit removal efficiency. From the above, it is clear that the low volatile solids fraction of the mixed liquor and the high sludge production are both attributable to:

- i. inadequate capacity, and poor design and maintenance of grit removal units, which are often the most neglected parts of WWTPs, and added as afterthoughts;
- ii. in many places in China the sewage contains high ISS concentrations with parts comprising fine material with diameters below 200 µm (Dai 2017; Ji 2017; Zheng 2017), which are difficult for conventional grit units to remove as they are targeted mainly at material exceeding 200 µm diameter and 2.7 g/cm³ (Tchobanoglous *et al.* 2003).

The corresponding actions should be studying current grit removal performance, including ISS mass loading and removal efficiency, and maintaining grit removal units regularly. It is possible to achieve an MLVSS fraction of between 55 and 60% with a conventional grit removal unit under normal operating conditions. Upgrading existing conventional grit removal units with increased hydraulic retention time (Zheng 2019) should also be considered for improved efficiency. Site-specific investigation with respect to equipment capable of removing particulate matter smaller than 200 µm should also be conducted. The high concentrations of fine ISS in Chinese sewage, which have deleterious effects on the performance of many Chinese WWTPs, suggest that specific research on grit removal would be worthwhile.

Key steps suggested in relation to grit removal at Chinese WWTPs are:

- i. conducting a national survey of the volatile solids fractions of sewage and mixed liquor in municipal WWTPs; grit removal unit performance can be estimated on the basis of these two fractions;
- ii. reducing ISS accumulation in the process by improving the efficiency of grit removal units; and,
- iii. setting the action target of MLVSS fraction at 55% for small WWTPs and 60% for large ones (i.e. capacity ≥50,000 m³/d), in order to try to achieve a roughly 10% increase in the MLVSS by upgrading grit removal efficiency.

Sludge fermentation. Maximizing the use of internal carbon should be the first objective in addressing carbon shortages in BNR processes. Full utilization of readily biodegradable soluble COD for nutrient removal should be explored as demonstrated in Zurich WWTP (Dominguez & Gujer 2006). Utilization of biodegradable particulate COD through PS fermentation (Barnard *et al.* 2017) is one practice that could be expanded. Figure 1 shows an average 40 mg-VFA/L increase arising from full-scale PS fermentation. Return activated sludge (and on-line mixed liquor) fermentation has been used widely in the USA and Europe to enhance BNR (Barnard *et al.* 2017).

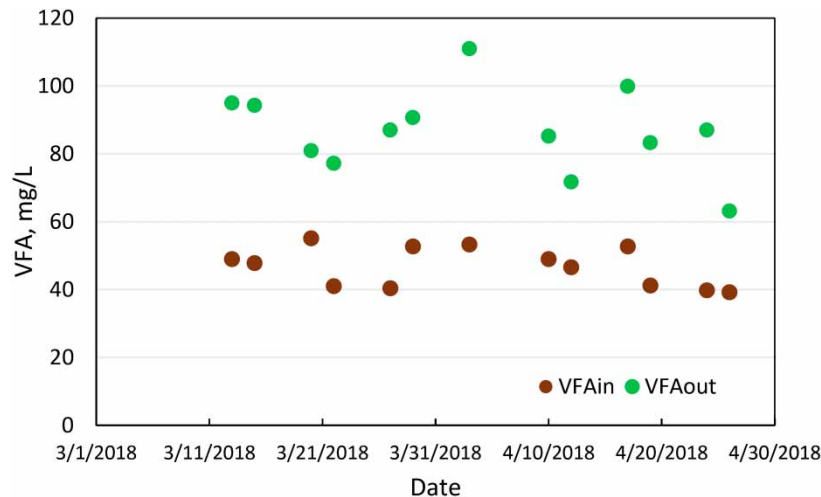


Figure 1 | VFA in and out in a full-scale primary sludge fermentation showing average increase 40 mg-VFA/L [$VFA_{out} - VFA_{in}$], temperature 16–18 °C, net release of NH_4-N and P of 2 and 1 mg/L, respectively.

Low carbon requirement nutrient removal processes. Processes like BCFS (biological–chemical phosphorus and nitrogen removal) (Barat & van Loosdrecht 2006), SANI (van Loosdrecht & Chen 2012) and MABR (membrane aerated biofilm reactors) (Houweling & Daigger 2019) should be considered with respect to nutrient removal in low carbon situations. BCFS and MABR have been applied at full-scale, but SANI only at pilot-scale to date. Since their application in China is still limited, pilot- or demonstration- scale tests will be needed. Replication of the recent full-scale partial denitrification and anammox at Xian WWTP No. 4 (Li *et al.* 2019) should also be pursued.

Future considerations

Energy recovery. For those WWTPs with suitable treatment capacity and relatively high influent COD concentrations (e.g. >300 mg/L), the volatile solids fraction is the key to applying AD. Given an initial volatile solids fraction of 55%, an increase of 10% in the mixed liquor can lead to an approximately 20% increase in biogas production (Ji 2017; Cao & Daigger 2019). At the same time, abrasive wear and pipe clogging are reduced significantly, largely eliminating the technological obstacles to AD application. The electricity recovered from AD via CHP could save up to about 30% of that needed to operate the WWTPs (Kroiss & Cao 2014). The Bailonggang WWTP in Shanghai – capacity 2,000,000 m³/d – (Hu 2019) with influent COD concentration, and Zurich WWTP with primary effluent COD concentration of around 250 mg/L (CUWA 2017; Dominguez & Gujer 2006) and both using AD for energy recovery, confirm that the approach is feasible. Given that about half of the sewage in China is treated in plants with capacities exceeding 100,000 m³/d (CUWA 2017), energy recovery from AD would be significant even if only half of them applied it. For smaller plants, dewatered sludge could be sent either to larger plants or regional sludge treatment centres for energy recovery.

Reducing carbon expenditure. The target is to obtain net 25 mg-COD/L through sludge fermentation. This is equivalent to a reduction in nitrate concentration of about 5 mg-N/L in the final effluent, which will help in achieving final effluent TN concentrations <10 mg/L, with little or no carbon addition.

Reducing sludge production. A 10% increase in VSS/TSS fraction due to grit removal improvement can be expected to yield an approximately 30% reduction in sludge production (Cao & Daigger 2019). With VSS removal of between 40 and 50% during AD (Grady *et al.* 1999), sludge production can be reduced by up to 50%. This implies that the amount of sludge produced at national scale could be reduced by 25%, if half of the WWTPs achieve ISS reduction and apply AD. In conjunction with

the increased energy recovery and reduced chemical costs for nutrient removal, the sustainability of China's WWTPs could be improved substantially.

Enhancing results-oriented applied research. Strong R & D research is indispensable for removing bottlenecks and achieving municipal wastewater treatment targets. Detailed feasibility studies and planning are needed at the start. Sewage characteristics, especially poorly biodegradable particulates, and nitrate up-take rates etc, will help to determine whether PS is needed or not. Biochemical volatile fatty acid potential (BVFAP) tests (Zhou *et al.* 2018a, 2018b) should be conducted to evaluate the feasibility of fermentation of both primary and activated sludges.

Studies of process efficiency, control, materials and maintenance requirements, etc, can only be carried out under site-specific, dynamic conditions. China has achieved startling progress in water science research in the last few years, now it is time to take further steps in engineering research towards sustainable municipal wastewater treatment.

CONCLUDING REMARKS

In recent decades China has achieved remarkable progress in urban sanitation. However, municipal sewage treatment still confronts low efficiencies in energy recovery, increasing costs for nutrient removal and high sludge production, all attributable to the unique sewage characteristics of high ISS, and low COD and C/N ratio. This study has shown the cause-effect relationships between the sewage characteristics and the low efficiency performance of municipal WWTPs. It appears that integrated guidelines for the design and operation of WWTPs, tailored to local sewage characteristics, are needed. Cost-effective measures and solutions should be identified for quick action to improve the sustainability of WWTPs in parallel to sewer rehabilitation. Efficient grit removal, sludge fermentation and low carbon BNR processes are proposed above, and the potential benefits estimated. The need to conduct results-oriented research on municipal wastewater treatment is stressed.

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