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Domestic Wastewater Treatment: Difficulties and Reasons, and Prospective Solutions—China as an Example

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Abstract

During the last three decades, China has attained noteworthy advances in municipal sanitation. The country has constructed a highly large infrastructure for treating wastewater, with 94.5% treatment coverage in urban areas and legally mandated nation-wide full nutrient removal applied. Nevertheless, domestic wastewater treatment plants (WWTPs) are yet defied with problems rooted in the singular sewage properties. Recently, Cao *et al.* [1] compared energy recovery, price of nutrient reduction and sludge formation among Chinese urban WWTPs and those in nations with longer wastewater treatment traditions, and underlined the cause-effect relationships among Chinese sewage properties—high inorganic suspended solids (ISS) loads, and low COD and C/N ratio, and municipal WWTP process performance in China. Combined design and running guidelines for domestic WWTPs are crucial in relation to the singular sewage properties in China. Cost-efficient actions and solutions are suggested by Cao *et al.* [1], and the likely advantages of enhancing the sustainability of urban WWTPs in China are evaluated.

Subject Areas

Environmental Sciences

Keywords

Wastewater Treatment, Wastewater Treatment Plants (WWTPs), Inorganic Suspended Solids (ISS), Volatile Suspended Solids (VSS), Anaerobic Digestion (AD)

1. Introduction

During the last three decades, China has attained an extraordinary advance in municipal sanitation [1]. Annual domestic sewage treatment potential amounted to 49.2 × 10^9 m^3, with 94.5% treatment coverage in urban areas in 2017 [1]. Nutrient (nitrogen and phosphorus) elimination is needed legally and has been applied at the national level. Nevertheless, small energy recuperation is carried out, nutrient elimination is costly, and sludge formation is elevated at municipal wastewater treatment plants (WWTPs). The unique properties of Chinese sewage/wastewater are the major reason for the low performance of municipal WWTPs [1]. Sewer leakage is the first determining factor conducting to China's unique sewage properties [2]. In view of the hard missions implicated, and the great investment and long periods required for sewer rehabilitation, cost-efficient and rapid works are necessitated to enhance the sustainability of Chinese domestic sewage treatment.

Cao *et al.* [1] focused on three aims: 1) to match energy recovery, nutrient reduction, and sludge formation at municipal WWTPs in China with those in other nations with longer wastewater treatment traditions; 2) to discover the cause-effect link among Chinese sewage properties and the technology efficiency of municipal WWTPs; and 3) to suggest cost-efficient procedures and solutions to elevate the sustainability of municipal WWTPs.

2. Methodology

In China, energy recuperation is founded on comparisons of WWTPs employing anaerobic digestion (AD), and combined heat and power (CHP) in China, and Europe, USA and Singapore. Because primary settling tanks and AD are utilized rarely in China, sludge formation is mostly founded on observed biomass yield coefficients and influent inorganic suspended solids (ISS) gathering in the technique is evaluated following mass balance [3].

3. Results and Discussion

3.1. Municipal Wastewater Treatment—Sustainability

Table 1 illustrates that less than 5% of Chinese domestic WWTPs employ AD [3], which is very small contrasted to Europe, USA and Singapore. This shows restricted energy recovery from internal sources via AD and/or CHP in China, even if the technique has been accessible in the nations with longer wastewater treatment traditions [4]. Failure to utilize AD conducts not only to sludge stabilization problems [3], but also augmented sludge generation (lack of volatile suspended solids (VSS) demolition in AD or lime, etc., addition for stabilization) and hygiene issues, along with sludge disposal and reuse problems [3].

With a view to satisfy 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,

Table 1. Proportion municipal WWTPs with AD in China and other countries (%) [1].

Country	China	Denmark	France	Germany	Netherlands	Singapore	Sweden	Switzerland	UK	USA
Proportion municipal WWTPs with AD	<5	52	39	87	66	100	56	95	97	68

TP < 0.3 mg/L applied in sensitive regions in numerous provinces), carbon injection (and chemicals for phosphorus removal) is applied in several WWTPs in China [3] despite the restricted usage of primary settling (PS) tanks. Basically, this is attributed to the small C/N ratio of the incoming sewage as for more usual sewage, traditional biological nitrogen reduction methods may attain effluent TN < 10 mg-N/L without carbon dosing [3]. Due to chemical usage, chemicals include the second highest operating cost (after power) in several plants [3]. Chemical prices are predicted to augment more, if stricter nutrient discharge standards (such as TN < 5 mg-N/L and TP < 0.1 mg-P/L) are applied. This will apply more economic burdens on plant operations and local authorities, apart from which, augmented chemical injection is unsustainable when the primary energy employed and corresponding greenhouse gas emissions are taken into account [5].

Wastewater treatment sludge consists of excess biomass, refractory particulate chemical oxygen demand (COD) and mineral particles (ISS) [6] [7] [8] [9]. Sludge formation is dictated by the wastewater properties, technique and site nature. **Table 2** shows the annual average sludge formation (dry solids (DS) based) related to COD elimination in wastewater treatment in China in 2015, 2016 and 2017 [1]. The three-year average is 0.69 kg/kg-COD reduced. Taking into account the restricted usage of PS 10% - 20% [1] and AD (<5%), the sludge formation per kg/COD reduced may be considered as the observed sludge yield (coefficient) from the activated sludge process [3]. The sludge formation yield founded on the sewage composition in China in 2017 [2], assuming an influent VSS/TSS ratio of 80% [10] and dominating biological nutrient reduction method, is evaluated following Paul *et al.* [11]. 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) must be 0.48 kg/kg COD eliminated. This comprises 30% more sludge than traditional biological nitrogen removal (BNR) (3.7 kg/kg COD eliminated) because of metal injection for chemical P elimination. The real 0.69 kg/kg COD reduced is 44% more important than the 0.48 kg/kg COD reduced with the normal (80%) influent VSS/TSS ratio [1].

In China, investigations of sludge formation in WWTPs have depicted that WWTPs usually yield approximately 0.48 kg-DS/kg COD reduced when the influent features are more or less normal; however, those with sludge yields of 0.69 or higher are treating sewage with abnormal features. It is probable that the high yield noted is because of extra mineral accumulation originating from the influent

Table 2. Chinese annual COD reduction and sludge generation and sludge observed yield coefficients for 2015, 2016 and 2017 [1].

	2015	2016	2017
COD eliminated	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 (DS)/COD eliminated, kg sludge/kg COD eliminated	0.69	0.62	0.77

[a]COD removed, kg × 10^{-1}/m^3, average of municipal WWTPs; [b]COD removed, kg × 10^9, all municipal WWTPs; [c]COD removed, kg × 10^9, all municipal WWTPs; [d]Sludge produced (DS), kg × 10^9, all municipal WWTPs; [f]Sludge produced (DS), kg × 10^9, all municipal WWTPs.

wastewater [1].

Average sludge yield in France, where 39% of WWTPs have AD, is 0.44 kg-/kg COD removed (calculated from 0.97 kg-/kg-BOD_5elim assuming 1 mg BOD_5 = 2.2 mg COD) [1]. 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% [12]. 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 [1].

3.2. Reasons for Low-Efficiency Efficiency: Distinctive Sewage Properties

Wastewater features are crucial in designing and modelling activated sludge processes [10] [13] [14] [15] [16]. Cao *et al.* [2] quantified the sewer system leakage portions in four cases, and proved that sewer leakage conducts to three sewage properties: high ISS, and low COD and C/N ratio, in China [1].

It has been illustrated that the influent VSS/TSS ratio of the WWTPs in many regions with reasonably well handled sewer systems in China is among 50 and 60%. This is under the 60% - 80% median interval [13], even if more information is needed for a national picture. The low influent ratios mentioned—COD/SS < 1 and BOD_5/SS = 0.3 - 0.5 in China [1] are also indicators of high ISS loads (sand, etc.) in the sewage. The influent ISS/TSS fraction has a direct effect on the mixed liquor volatile solids fraction (MLVSS/MLTSS) as depicted by Equation (1) [3] assuming no PS:

$$MLVSS/MLTSS = ISS_{IO} \times \left(\Theta_c/\tau\right) \quad (1)$$

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

Employing 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, showing the sensitivity of ISS to the VSS portion. Modelling illustrated that a 10% decrease in the influent ISS/TSS (increasing VSS/TSS) ratio can cause a 15% - 25% increase in the MLVSS fraction [1]. 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 [17]. The average volatile solids fraction reported in China is below 50% well below the normal 70% - 75% range [10]. This shows important inorganic solids input and accumulation, even taking into account the accumulation of minerals utilized to eliminate phosphorus chemically (volatile solids fraction 60%) [1].

A small MLVSS portion is harmful to both activated sludge and AD process efficiency. Considering a volatile solids portion of 70% as the comparison basis, the lower portion of 50% will need a volume augmentation of about 30% for the activated sludge tanks and AD. On the other hand, the activated sludge process SRT will be diminished. This may influence process efficiency negatively if the impact of elevated influent ISS was not taken into account in the first design, greatly leading to increased effluent ammonia in winter [1].

A small volatile solids portion in the AD feed diminishes the biogas production per unit effective volume (or per unit sludge). This would conduct to the requirement of addition volume, or the SRT and total biogas formation could be decreased. The integration of decreased biogas yield with solids depositing in AD, and pipe clogging provoked by sand and abrasive wear [18] [19] has conducted to the very small present implementation of AD in China. Of several parameters, the elevated ISS content of numerous wastewaters remains the principal technological hurdle to AD implementation in China [18] [19]. This further elevates the investment need for solids processing at municipal WWTPs [1]. Elevated ISS influent levels also lead to the necessity of supplementary capability 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 elevated sludge formation [3]. Modeling illustrated that when the influent ISS/TSS ratio decreases from 70 to 60%, or from 60 to 50%, sludge production (DS) decreases by about 30%, with or without PS [1]. In summary, high influent sewage ISS imposes multiple negative effects on municipal WWTP efficiency and operation [1].

More details about this scientific discussion may be found in [1].

3.3. Likely Solutions

3.3.1. Development of Integrated Guidelines for the Design and Operation of Municipal WWTPs

In reaction to China's unique sewage properties, guidelines for the design and running of municipal WWTPs are required. They have to combine problems of local sewage features, discharge requirements, location, treatment capacity, and energy, chemicals and sludge disposal costs, etc. As a system input, sewage features possess crucial contributions in the selection and design of the biological technique. Traditional processes may not be utilizable to remedy dilute sewage (like about 100 mg-COD/L) in areas of southern China; as an alternative, methods such as membrane-founded technique [20]-[25] or SANI (sulfate reduction, autotrophic denitrification, and nitrification [26] have to be think about. Denitrification amelioration with biodegradable particulate COD (via omitting PS) may be practical in warm climates, but not in cold zones [1].

Implementing AD for energy recovery in Chinese municipal WWTPs has to be first considered. In the USA at the turn of the century, it was economically possible to utilize AD in WWTP with capacities exceeding 100,000 m^3/d [4]. More newly, AD has begun to be economic in even smaller plants with capacities of 20,000 - 40,000 m^3/d. In Europe, they can yield economic benefits at around 10,000 m^3/d (50,000 PE) [4]. The economic feasibility of AD at a Chinese municipal WWTP has to be evaluated in the context of local circumstances [1].

3.3.2. Suggested Actions

Taken into account the long period needed for sewer rehabilitation and the present status of urban WWTPs, cost-efficient actions and solutions to ameliorate WWTP efficiency necessitate to be figured out and applied while integration guidelines are formulated. Possible amelioration in grit removal and sludge fermentation and the usage of AD and CHP are defined below. Considering the influence of plant size on economic advantages and cost-effectiveness, grit removal enhancement appears valuable for all WWTPs; however, sludge fermentation and the implementation of AD and CHP for energy recuperation would be appropriate for relatively large WWTPs with relatively high influent COD levels (such as 250 mg/L) [1].

a) Enhancement of grit removal efficiency

From the above, it is obvious that the low volatile solids portion of the mixed liquor and the elevated sludge formation are both attributable to [1]:

i. unsuitable capacity, and poor design and maintenance of grit removal units, which are usually the most neglected parts of WWTPs, and added as afterthoughts;

ii. in numerous regions in China, the sewage carries elevated ISS levels with parts including fine material with diameters below 200 μm [1], which are hard for traditional grit units to eliminate since they are targeted mostly at material exceeding 200 μm diameter and 2.7 g/cm^3 [27].

The corresponding measures have to be investigating current grit removal efficiency, comprising ISS mass loading and elimination performance and maintaining grit reduction units orderly. It is likely to attain an MLVSS portion of 55% - 60% with a traditional grit removal unit under normal running conditions. Upgrading present traditional grit removal units with augmented hydraulic retention time [1] has as well to be adopted for ameliorated performance. Site-specific investigation with respect to equipment capable of reducing particulate matter smaller than 200 μm has as well to be performed. The elevated levels of fine ISS in Chinese sewage, which possess harmful impacts on the efficiency of numerous Chinese WWTPs, propose that particular investigation on grit reduction would be of use.

Critical stages proposed relating to grit reduction at Chinese WWTPs are [1]:

i. performing a national investigation of the volatile solids portions of sewage and mixed liquor in domestic WWTPs; grit reduction unit efficiency can be evaluated on the basis of these two portions;

ii. decreasing ISS accumulation in the process via enhancing the performance of grit reduction units; and

iii. setting the action objective of MLVSS portion at 55% for small WWTPs and 60% for large ones (*i.e.*, capacity > 50,000 m^3/d), with a view to attempting to attain a roughly 10% increase in the MLVSS by upgrading grit removal efficiency.

b) *Sludge fermentation*

Increasing the usage of internal carbon has to be the primary aim in dealing with carbon lacks in BNR processes [1]. Complete utilization of readily biodegradable soluble COD for nutrient removal has to be studied as established in Zurich WWTP [28]. Employing biodegradable particulate COD via PS fermentation [29] stays one practice that may be developed. **Figure 1** illustrates an average of 40 mg-VFA/L augmentation arising from full-scale PS fermentation. Return activated sludge (and on-line mixed liquor) fermentation has been utilized broadly in the USA and Europe to improve BNR [29].

c) *Low carbon requirement nutrient removal processes*

Techniques such as BCFS (biological–chemical phosphorus and nitrogen removal) [30], SANI [26] and MABR (membrane aerated biofilm reactors) [1] have to be examined in point of view of nutrient elimination in low carbon

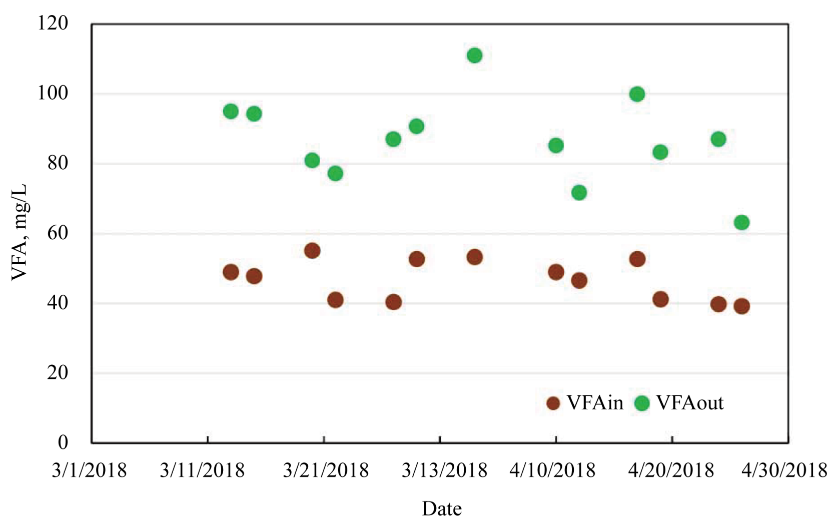

Figure 1. VFA in and out in a full-scale primary sludge fermentation showing average increase 40 mg-VFA/L [VFAout-VFAin], temperature 16 - 18˚C, net release of NH_4-N and P of 2 and 1 mg/L, respectively [1].

circumstances. BCFS and MABR have been implemented at full-scale; however, SANI simply at pilot-scale to date. As their usage in China remains still restricted, pilot or demonstration-scale trials will be necessitated [1].

3.3.3. Future Considerations

a) *Energy recovery*

For those WWTPs with convenient treatment capability and comparatively elevated influent COD levels (such as 250 mg/L), the volatile solids portion is the key to implementing AD. Taking into account a beginning volatile solids portion of 55%, an elevation of 10% in the mixed liquor may conduct to an around 20% augmentation in biogas generation [31]. In the same period, abrasive wear and pipe clogging are decreased importantly, widely diminishing the technological hurdles to AD utilization. The electricity recuperated from AD through CHP could save up to around 30% of that required to run the WWTPs [4]. The Bailonggang WWTP in Shanghai, capacity 2,000,000 m^3/d, [1] with influent COD level, and Zurich WWTP with primary effluent COD level of about 250 mg/L [1] and both employing AD for energy recovery, prove that the procedure is practical. Assuming that approximatively half of the sewage in China is treated in plants with capacities surpassing 100,000 m^3/d [1], energy recovery from AD would be important even if only half of them applied it. For smaller plants, dewatered sludge could be sent either to larger plants or regional sludge treatment centers for energy recovery [1].

b) *Reducing carbon expenditure*

The objective is to reach net 25 mg-COD/L via sludge fermentation. This is equivalent to a diminution in nitrate level of around 5 mg-N/L in the final effluent, which will assist in obtaining final effluent TN levels, 10 mg/L, with small or no carbon introduction [1].

c) *Reducing sludge production*

A 10% raise in VSS/TSS portion thanks to grit removal amelioration can be anticipated to provide an around 30% reduction in sludge generation [31]. With VSS reduction of among 40 and 50% throughout AD [3], sludge formation can be diminished by up to 50%. This implicates that the quantity of sludge generated at the national scale could be decreased by 25% if half of the WWTPs attain ISS reduction and implement AD. In conjunction with the augmented energy recovery and decreased chemical prices for nutrient removal, the sustainability of China's WWTPs could be enhanced greatly [1].

d) *Enhancing results-oriented applied research*

Powerful R & D research is necessary for reducing hurdles and attaining domestic wastewater treatment aims [1] [32] [33]. Comprehensive feasibility investigations and planning are required at the beginning [34] [35]. Sewage properties, particularly poorly biodegradable particulates, and nitrate uptake rates, etc., will assist to decide if PS is necessitated or not. Biochemical volatile fatty acid potential (BVFAP) trials [36] have to be performed to assess the feasibility of fermentation of both primary and activated sludges.

Investigating process efficiency, control, materials and maintenance requirements, etc., may only be performed below site-specific, dynamic circumstances [37]. China has attained spectacular advance in water science study in the recent decade; at present, it is time to advance in engineering investigation towards sustainable urban wastewater treatment [1].

4. Conclusions

From this work, the following conclusions can be drawn:

1) China has attained exceptional advances in municipal sanitation. Nevertheless, urban sewage treatment yet challenges low performances in energy recovery, augmenting prices for nutrient reduction and elevated sludge formation, all related to the singular sewage characteristics of high ISS, and low COD and C/N ratio [1].

2) Cao *et al.* [1] illustrated the cause-effect relationships among the sewage features and the low-efficiency performance of domestic WWTPs. It seems that combined guidelines for the design and running of WWTPs, adopted to local sewage properties, are required. Cost-effective actions and solutions have to be defined for rapid action to ameliorate the sustainability of WWTPs in parallel to sewer rehabilitation. Efficient grit reduction, sludge fermentation, and low carbon BNR techniques are suggested, and the possible advantages evaluated. The necessity to carry out a results-oriented investigation on domestic wastewater treatment is underlined.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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