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Review

Technologies for reducing sludge production in wastewater treatment plants: State of the art

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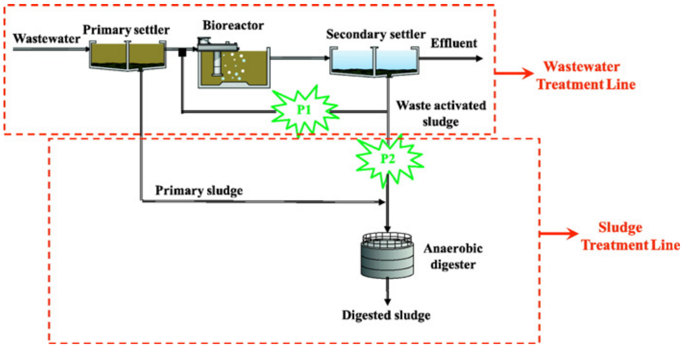
HIGHLIGHTS

- State-of-the-art sludge reduction technologies were reviewed.
- Advantages and disadvantages of sludge reduction technologies were discussed.
- Free nitrous acid technology seems good in wastewater treatment line.
- Thermal pretreatment and TPAD are superior in sludge treatment line.
- Future perspectives of sludge reduction technologies were elucidated.

GRAPHICAL ABSTRACT



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ABSTRACT

This review presents the state-of-the-art sludge reduction technologies applied in both wastewater and sludge treatment lines. They include chemical, mechanical, thermal, electrical treatment, addition of chemical uncoupler, and predation of protozoa/metazoa in wastewater treatment line, and physical, chemical and biological pretreatment in sludge treatment line. Emphasis was put on their effect on sludge reduction performance, with 10% sludge reduction to zero sludge production in wastewater treatment line and enhanced TS (total solids) or volatile solids removal of 5–40% in sludge treatment line. Free nitrous acid (FNA) technology seems good in wastewater treatment line but it is only under the lab-scale trial. In sludge treatment line, thermal, ultrasonic (<4400 kJ/kg TS), FNA pretreatment and temperature-phased anaerobic digestion (TPAD) are promising if pathogen inactivation is not a concern. However, thermal pretreatment and TPAD are superior to other pretreatment technologies when pathogen inactivation is required. The new wastewater treatment processes including SANI®, high-rate activated sludge coupled autotrophic nitrogen removal and anaerobic membrane bioreactor coupled autotrophic nitrogen removal also have a great potential to reduce sludge production. In the future, an effort should be put on the effect of sludge reduction technologies on the removal of organic micropollutants and heavy metals.

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Contents

1. Introduction

Biological wastewater treatment plants (WWTPs) have been employed throughout the world to treat municipal wastewater. Despite the fact that it is efficient in removing organics, large amounts of excess sludge are generated. For example, the average annual production of excess sludge is 3 million wet tons in Australia, and 240 million wet tons in Europe, USA and China combined (Pritchard et al., 2010). The main methods for sludge disposal have been and still are landfill, agricultural use and incineration, all incurring very large costs (e.g. $30–70 per wet ton in Australia and €30–100 per wet ton in Europe) (Batstone et al., 2011). Therefore, reducing sludge production in WWTPs has become a hot topic for both practitioners and researchers.

The excess sludge can be classified into primary sludge and secondary sludge (or waste activated sludge, i.e. WAS) (Metcalf and Eddy, 2003). Primary sludge is the sludge composed of settleable solids removed from raw wastewater in primary settler. WAS is the sludge produced by biological process such as activated sludge process. WAS mainly consists of bacteria growing on organic and inorganic substances, extracellular polymeric substances (EPS) excreted by bacteria, recalcitrant organics originating from wastewater or formed during bacterial decay, and inorganics from wastewater. In general, the biodegradability of primary sludge is high and thus it would be quite difficult to further enhance its degradation through pretreatment technologies (Carrere et al., 2010). In contrast, WAS has low biodegradability (Carrere et al., 2010). Therefore, lots of technologies have been developed to reduce WAS production.

For the time being, technologies for achieving sludge reduction can be divided into two types, (a) reducing sludge production in wastewater treatment line, and (b) achieving sludge reduction in sludge treatment line (see Fig. 1). In general, they are not implemented simultaneously in the same WWTP. For instance, reducing sludge production in wastewater treatment line is applied in the small WWTPs where anaerobic digesters do not exist, whereas achieving sludge reduction in sludge treatment line is implemented in the large WWTPs with anaerobic digesters (Perez-Elvira et al., 2009; US EPA, 2011).

The commonly used approach for reducing sludge production in wastewater treatment line is to implement technologies to treat return activated sludge, which is then recirculated to the main-stream bioreactor for further biodegradation (see P1 in Fig. 1). These treatment technologies include chemical treatment, mechanical treatment, thermal treatment and electrical treatment (Camacho et al., 2005; Heinz, 2007; Mohammadi et al., 2011; Wang et al., 2013a; Semblante et al., 2014; Romero et al., 2015). They cause cell lysis with subsequent release of intracellular and extracellular substances, which become substrate available for biodegradation (van Loosdrecht and Henze, 1999; Hao et al., 2010), whereby sludge reduction is achieved. In addition to the treatment technologies, the other technologies for reducing sludge production in wastewater treatment line include addition of chemical uncoupler, and predation of protozoa and metazoa (Feng et al., 2014; Basim et al., 2016; Xiao et al., 2016; Zhu et al., 2016).

In the sludge treatment line, sludge is subject to thickening, stabilization, dewatering and final disposal. Anaerobic digestion is the most commonly used sludge stabilization method, which is used to reduce the mass of sludge (Appels et al., 2008). However, anaerobic digestion is generally limited by the poor biodegradability of WAS (Appels et al., 2008; Wang et al., 2013b). Therefore, analogous to the technologies applied in wastewater treatment line, a number of pre-treatment technologies have been integrated into the sludge treatment line before anaerobic digestions to achieve sludge reduction (P2 in Fig. 1). They include physical pre-treatment, chemical pre-treatment and biological pretreatment (Ge et al., 2011; Bolzonella et al., 2012; Abelleira-Peraira et al.,

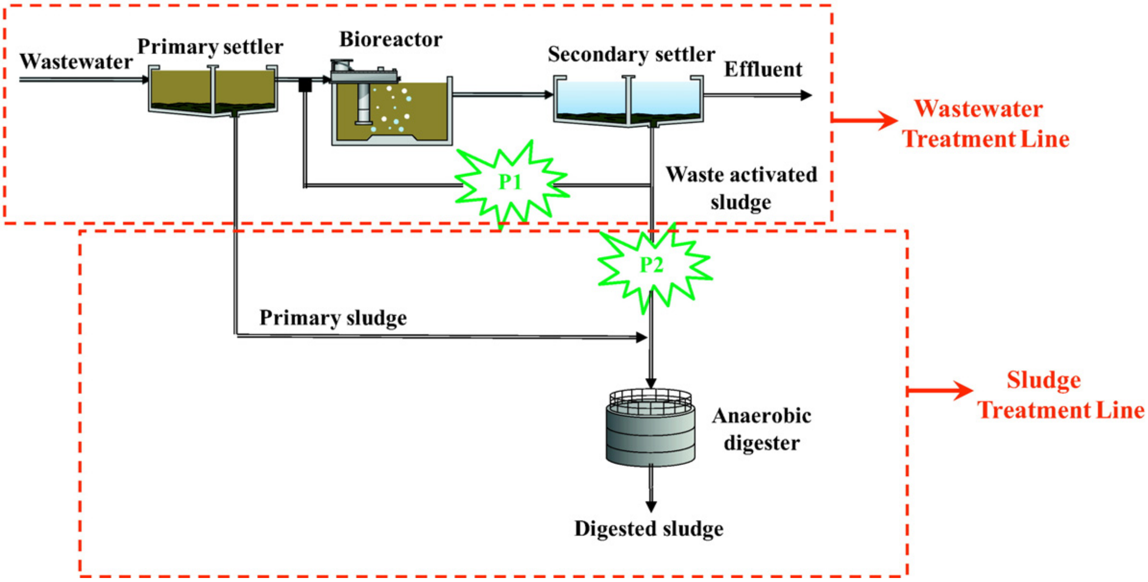

Fig. 1. Potential locations for sludge reduction technologies in a typical wastewater treatment plant (WWTP). P1 indicates the location integrated into wastewater treatment line. P2 indicates the location applied in sludge treatment line. P1 is generally implemented in the small-size WWTPs where anaerobic digesters do not exist. P2 is generally implemented in the large WWTPs.

2015; Martinez and Gude, 2015; Silvestre et al., 2015; Yeneneh et al., 2015; Zahedi et al., 2016).

Although sludge reduction technologies have been documented, the state-of-the-art technologies and treatment process design for reducing sludge production have not been reviewed. Also, the comprehensive review on sludge reduction technologies in both wastewater treatment line and sludge treatment line is still lacking. Therefore, this review aims to provide a state-of-the-art review of the technologies for reducing sludge production in WWTPs. The various technologies for reducing sludge production in both wastewater treatment line and sludge treatment line were first reviewed with the sludge reduction performance elucidated. The advantages and disadvantages of them were then discussed. The new wastewater treatment process designs that could achieve sludge reduction were proposed. The future perspectives of sludge reduction technologies were also put forward.

2. Reducing sludge production in wastewater treatment line

Reducing sludge production in wastewater treatment line is generally carried out in the small-size WWTPs, in which anaerobic digester does not exist. It is achieved through treatment technologies, addition of chemical un-coupler, and predation of protozoa and metazoa.

2.1. Reducing sludge production through treatment technologies

Reducing sludge production through treatment technologies is generally achieved by implementing treatment technologies to treat return activated sludge, which is then recycled to the main stream bioreactor for further biodegradation based on cell lysis-cryptic growth. The growth of bacteria utilizing the lysates of dead cells is named as cryptic growth (van Loosdrecht and Henze, 1999; Hao et al., 2010). When treatment technologies are adopted, microbial cells are subject to lysis or death, in which intracellular and extracellular materials are released. The released materials are utilized by bacteria for cell growth and maintenance, which results in a reduction in sludge production. The treatment technologies include chemical treatment, mechanical treatment, thermal treatment and electrical treatment.

2.1.1. Chemical treatment

Chemical treatment mainly consists of oxidation and free nitrous acid (FNA) treatment. Ozonation is the primary approach for oxidation treatment. Other oxidation treatment methods include chlorination, chlorine dioxide oxidation and Fenton oxidation.

Reducing sludge production using ozonation in the wastewater treatment line was proposed in the mid 90s. This has been successfully applied in the full-scale WWTPs. Ozonation can result in sludge disintegration, cell destruction, as well as solubilisation and mineralization of particulate and soluble compounds (Egemen et al., 1999; Gardoni et al., 2011; Romero et al., 2015). This is via either direct ozone oxidation or the formation of another strong oxidant - hydroxyl radicals (HO•), or combination of the above. Table 1 and Table S1 summarize the sludge reduction results achieved by ozonation treatment in the wastewater treatment line. In general, ozonation can achieve a sludge reduction of at least 10% or even zero sludge production. While implementing ozonation, the ozone concentration would be in the range of 0.01–0.74 g O_3/g TSS (TSS: total suspended solids). Chlorine, chlorine dioxide and Fenton reagents are also strong oxidizers. They have been applied to reduce sludge production at lab-scale systems, as summarized in Table 1 and Table S1. The applied chlorine concentration is typically from 0.066 to 0.23 g Cl_2/g TSS, resulting in a sludge reduction of 45–63%. Fenton oxidation has also been employed as an approach for sludge reduction due to its excellent behavior in the oxidation of organic substances. In Fenton reaction, H_2O_2 and Fe^{2+} react at low pH (around 3.0) to produce hydroxyl radicals (i.e. HO•), which are capable of destructing organic materials (He and Wei, 2010).

Free nitrous acid (FNA i.e. HNO_2) treatment is a novel sludge treatment technology to reduce sludge production, which is only applied at lab scale till now. Pijuan et al. (2012) showed that FNA, at parts per million (i.e. mg/L) levels, had a strong biocidal effect on the bacteria in WAS. It has been demonstrated that 50%–80% of the bacterial cells in WAS could be damaged by FNA at 1.0–2.0 mg N/L for 24–48 h. Based on the biocidal effect of FNA, Wang et al. (2013a, 2014a) proposed the FNA-based sludge reduction technology, as summarized in Table 1 and Table S1. In general, a sludge reduction of 11–28% could be achieved while part of the return activated sludge was treated by FNA at 1.35–2.0 mg N/L.

Table 1
Summarized results of sludge reduction technologies in wastewater treatment line.

Treatment technologies	Wastewater	Treatment conditions	Scale	Results
Ozone (chemical)[1]	SW[a]/RW[b]	0.01–0.74 g O_3/g TSS[c]	Lab/Pilot/Full-scale	Sludge reduction of 10% to zero sludge production
Chlorine (chemical)[2]	SW	0.066–0.23 g Cl_2/g TSS	Lab-scale	Sludge reduction of 45–65%
Chloride dioxide (chemical)[3]	SW	0.01 g ClO_2/g TSS	Lab-scale	Sludge reduction of 36%
Fenton (chemical)[4]	SW	$H_2O_2 + Fe^{2+}$	Lab-scale	Sludge reduction of 96%
Free nitrous acid (FNA) (chemical)[5]	SW	1.35–2.0 mg HNO_2-N/L	Lab-scale	Sludge reduction of 11–28%
Ultrasonic(mechanical)[6]	SW/RW	20–31 kHz; 1.5–15 min	Lab/Pilot/Full-scale	Sludge reduction of 25–91%
High pressure homogenization (mechanical)[7]	SW/RW	Pressure: 300 bar; 10,700 kJ/kg TSS	Lab/Pilot-scale	Sludge reduction of 20–94%
Thermal[8]	SW/RW	90–95 °C; 45–180 min	Lab/Pilot-scale	Sludge reduction of 60%
Electrical[9]	RW	1650 kJ/kg TSS	Pilot-scale	Sludge reduction of 27–45%
Un-coupler[10]	SW/RW	0.4–100 mg/L	Lab/Pilot-scale	Sludge reduction of 16–86%
Predation[11]	SW/RW	Not applicable	Lab/Pilot/Full-scale	Sludge reduction of 12–75%

[a] Synthetic wastewater.
[b] Real wastewater.
[c] Total suspended solid.
[1] References: Yasui and Shibata, 1995; Yasui, 1996; Sakai et al., 1997; Egemen et al., 1999; Huysmans et al., 2001; Deleris et al., 2002; He et al., 2003; Song et al., 2003; Lee et al., 2005; He et al., 2006; Suzuki et al., 2006; Dytczak et al., 2006; Egemen Richardson et al., 2009; Gardoni et al., 2011; Romero et al., 2015.
[2] References: Saby et al., 2002; Takdastan et al., 2009, 2010.
[3] References: Wang et al., 2011.
[4] References: He and Wei, 2010.
[5] References: Wang et al., 2013a, 2014a.
[6] References: Zhang et al., 2007; Neis et al., 2008; He et al., 2011; Mohammadi et al., 2011.
[7] References: Camacho et al., 2002; Rai and Rao, 2009.
[8] References: Canales et al., 1994; Camacho et al., 2005.
[9] References: Heinz, 2007.
[10] References: Mayhew and Stephenson, 1998; Strand et al., 1999; Low et al., 2000; Chen et al., 2002; Yang et al., 2003; Ye and Li, 2005; Chase et al., 2007; Rho et al., 2007; Chen et al., 2008; Aragon et al., 2009; Song et al., 2010; Chong et al., 2011; Guo et al., 2014; Feng et al., 2014; Zuriaga-Agustí et al., 2016; Xiao et al., 2016.
[11] References: Ratsak, 1994; Wei and Liu, 2005; Elissen et al., 2006; Guo et al., 2007; Huang et al., 2007; Hendrickx et al., 2009; Lou et al., 2011; Tamis et al., 2011; Zhang et al., 2013; Basim et al., 2016; Zhu et al., 2016.

2.1.2. Mechanical treatment

Mechanical treatment can be fulfilled using different mechanical equipments. Ultrasonic treatment and high pressure homogenization are the primary mechanical treatment technologies.

Ultrasonic treatment is based on cavitation and the formation of hydroxyl radicals (i.e. HO•). Powerful ultrasound leads to acoustic cavitation in liquids, in which millions of small bubbles collapse to generate high pressure (500 bar), temperature (5000 K) and extreme shear forces that attack sludge mechanically (Zhang et al., 2007; Erden and Filibeli, 2009; Trzcinski et al., 2015). Ultrasonic treatment produces hydroxyl radical as well, which is highly oxidative and can cause sludge breakdown. Ultrasonic treatment has been applied at full scale to reduce sludge production. The frequency for ultrasonic treatment is usually in the range of 20–31 kHz, leading to a sludge reduction of 25–91%, as shown in Table 1 and Table S2.

High pressure homogenization is the alternative mechanical treatment technology. While sludge enters high pressure homogenizer, its speed rises to fifty times of its original speed, which results in cavitation and collisions among sludge particles (Rai and Rao, 2009). These will subsequently induce sludge disintegration and cell destruction. In contrast to the ultrasonic treatment, high pressure homogenization is only applied at pilot scale with a sludge reduction of 20–94%, as summarized in Table 1 and Table S2.

2.1.3. Thermal and electrical treatment

Thermal treatment destroys cell walls and thus enables intracellular materials to become available for the subsequent biodegradation (Camacho et al., 2005). However, due to the high costs for thermal treatment, only very few studies concerning its application in wastewater treatment line are available. Thermal treatment in wastewater treatment line is only applied at pilot scale. It is generally carried out at 90–95 °C, which caused 60% sludge reduction (see Table 1 and Table S2). Electrical treatment attacks the phospholipids (Heinz, 2007), which are the primary constituents of cell membrane. The consequent pore openings in the cell membranes induce cell rupture and then lysis, which results in the release of intracellular materials and thus promotes the subsequent biodegradation. Electrical treatment in wastewater treatment line is only applied at pilot scale and a sludge reduction of 27–45% was achieved after implementing electrical treatment to the return activated sludge at 1650 kJ/kg TSS (Heinz, 2007; Table 1 and Table S2).

2.1.4. Cannibal® process

The patented Cannibal® process combines physical and biological approaches to reduce sludge production (Novak et al., 2007; Johnson, 2008). Part of the return activated sludge first passes through an intermediate tank, drum screen, and hydrocyclone, which remove grit and other inert solids (i.e. physical approach). After physical approach, the sludge goes to an anaerobic/anoxic interchange reactor. The organics release occurred in the anaerobic/anoxic interchange reactor and was subsequently biodegraded in the mainstream bioreactor after being returned (i.e. biological approach) (Novak et al., 2007; Johnson, 2008). Novak et al. (2007) achieved a 60% lower sludge production in the Cannibal® process compared with the system without Cannibal® process.

2.2. Addition of chemical un-coupler

The anabolism of bacteria is coupled with the catabolism of substrate via rate limiting respiration. Nevertheless, catabolism and anabolism are not closely coupled sometimes, and uncoupled metabolism will happen if the biosynthetic process is rate limiting and instead the respiratory control does not exist (Hao et al., 2010). This induces the discrepancy in the energy level between catabolism and anabolism, and restricts the energy available for anabolism. Therefore, sludge yield will decrease. Addition of chemical metabolic un-couplers would uncouple bacterial catabolism from their anabolism, which has become an effective technology to achieve sludge reduction in the wastewater treatment line (Chong et al., 2011; Feng et al., 2014; Guo et al., 2014; Xiao et al., 2016; Zuriaga-Agustí et al., 2016). The commonly used chemical un-couplers include DNP (2,4-dinitrophenol), TCP (2,4,6-trichlorophenol), pNP (para-dinitrophenol), dNP (2,4-dinitrophenol), mNP (m-nitrophenol), oNP (o-nitrophenol), mCP (m-chlorophenol), pCP (p-chlorophenol), TCS (3,3′,4′,5-tetrachlorosalicylanilide) and THPS (tetrakis (hydroxymethyl) phosphonium sulfate). They are usually in the concentration range of 0.4 to 100 mg/L while being applied, leading to a sludge reduction of 16–86%, as summarized in Table 1 and Table S3. It should be noted that the chemical un-coupler would not be applied when healthy issue is considered.

2.3. Predation of protozoa and metazoa

Protozoa and metazoa that prey on bacteria are widely present in activated sludge. By preying on bacteria, they decrease the sludge production due to the dissipation of energy when energy transfers in the food chain. Sludge reduction via predation is generally achieved by adding protozoa and/or metazoa externally (Ratsak, 1994; Basim et al., 2016), which has been applied at full scale till now (see Table 1 and Table S4). *T. tubifex*, *Lumbriculus variegates* and *Tubificidae* are the commonly used protozoa/metazoa, through which a sludge reduction of 12–75% has been reported (Table 1 and Table S4). It should be pointed out that reducing sludge production via predation of protozoa and metazoa generally happens in the WWTPs with a long sludge retention time, under which the protozoa and metazoa would get sufficient time to grow.

3. Achieving sludge reduction in sludge treatment line

Achieving sludge reduction in sludge treatment line is generally carried out in the WWTPs where anaerobic digesters exist. Sludge reduction is achieved through adding a sludge pretreatment unit prior to anaerobic digester, in which enhanced sludge degradation would be achieved. In anaerobic digesters, the enhanced sludge degradation can be reflected by both enhanced TS (total solids) or VS (volatile solids) removal and improved methane/biogas production. The pretreatment technologies to achieve sludge reduction in sludge treatment line are based on physical, chemical and biological pretreatment.

It should be noted that pretreatment has also been used to enhance volatile fatty acid (VFA) production from anaerobic waste activated sludge fermentation by inhibiting methane production step (Zhou et al., 2013; Yang et al., 2015; He et al., 2016; Wu et al., 2017). The VFA can be used as a carbon source for biological wastewater treatment. However, this was not discussed in this review because its main purpose is to produce VFA instead of achieving sludge reduction. Also, VFA accumulation would compromise anaerobic methane production (unless the accumulated VFA was added to another anaerobic digester) and methane production is an important aim of anaerobic digestion.

3.1. Physical pretreatment

Physical pretreatment primarily consists of ultrasonic pretreatment, thermal pretreatment, microwave pretreatment, lysis-thickening centrifuge, stirred ball mill, high pressure homogenization and focused pulsed pretreatment.

3.1.1. Ultrasonic pretreatment

Similar to the wastewater treatment line, ultrasonic pretreatment has been applied to the sludge treatment line to achieve sludge reduction as well. Ultrasonic pretreatment is generally performed at 9–41 kHz (mostly at 20 kHz) for several seconds to 2.5 h (usually <1 h) with an enhanced VS removal of 9–36% and improved CH_4/biogas production of 24–138% (see Table 2 and Table S5). It was reported that ultrasonic pretreatment was only able to improve the sludge degradation rate and had no effect on the sludge degradation extent (Donoso-Bravo et al., 2010). Ultrasonic pretreatment has been applied to the full-scale

Table 2
Summarized results of sludge reduction technologies in sludge treatment line.

Pre-treatment	Sludge	Pretreatment conditions	Digestion conditions	Scale	Results
Ultrasonic[1]	MS[a]/WAS	9–41 kHz; 1–150 min	Semi-continuous, SRT[b]: 8–22 days; or Batch, 11–100 days	Lab/Pilot/Full-scale	Enhanced VS removal of 9–36%; enhanced CH_4/biogas production of 24–138%
Thermal[2]	MS/WAS	121–180 °C; 30–60 min	Semi-continuous, SRT: 5–20 days; or Batch, 7–28 days	Lab/Pilot/Full-scale	Enhanced TS/VS removal of 7–32%; enhanced CH_4 production of 14–90%
Microwave[3]	MS/WAS	2450 MHz; 700–1000 W; ~10 min	Semi-continuous, SRT: 5–25 days; or Batch, 18–33 days	Lab-scale	Enhanced TS/VS removal of 8–14%; enhanced CH_4 production of 30–84%
Lysis-thickening centrifuge[4]	MS/WAS	2250–3140 rpm	Semi-continuous, SRT: 35–40 days	Full-scale (70,000–150,000 PE)	Enhanced biogas production: 15–26%
Stirred ball mill[5]	MS/WAS	Ball velocity: 6–15 m/s; Ball diameter:0.25–0.35 mm	Semi-continuous, SRT: 7 days; or Batch, 21 days	Lab/Full-scale	Enhanced VS removal: 5%; enhanced biogas production: 10–21%
High pressure homogenizer[6]	MS	150–600 bar	Semi-continuous, SRT: 20 days; or Batch, 7 days	Lab/Full-scale	Enhanced biogas production of 18–64%
Ozonation[7]	MS/WAS	0.05–0.15 g O_3/g TS	Semi-continuous, SRT: 28 days; or Batch, 18–35 days	Lab/Full-scale	Enhanced TS/VS removal of 8–28%; enhanced CH_4 production of 25–110%
H_2O_2 [8]	MS	2.0 g H_2O_2/g VS; 24 h	Semi-continuous, SRT: 30 days	Lab-scale	Enhanced VS removal: 15%
Alkaline[9]	WAS	pH 10, 120–130 °C, 30–60 min; or pH 10, 34–36 °C, 8 days	Semi-continuous, SRT: 20 days; or Batch, 7–9 days	Lab-scale	Enhanced CH_4 production of 38–340%
FNA[10]	MS/WAS	1.0–2.5 mg HNO_2-N/L; 5–24 h	Batch, 40–44 days	Lab-scale	Enhanced CH_4 production of 15–56%
Biological[11]	WAS	60–70 °C; 9–48 h	Semi-continuous, 13–16 days; or Batch, 10 day	Lab/Pilot-scale	Enhanced VS removal of 7–11%; enhanced biogas/CH_4 production of 26–50%

[a] Mixed sludge (i.e. primary sludge + WAS).

[b] Sludge retention time.

[1] References: Tiehm et al., 1997, 2001; Wang et al., 1999; Chu et al., 2002; Onyeche et al., 2002; Bien et al., 2004; Bougrier et al., 2005; Xie et al., 2007; Braguglia et al., 2008, 2012; Neis et al., 2008; Salsabil et al., 2009; Erden and Filibeli, 2009; Perez-Elvira et al., 2008; Apul and Sanin, 2010; Salsabil et al., 2010; Saha et al., 2011; Kim and Lee, 2012; Zawieja and Wolny, 2013; Martinez and Gude, 2015; Trzcinski et al., 2015.

[2] References: Haug et al., 1978; Stuckey and Mc Carty, 1978; Li and Noike, 1992; Tanaka et al., 1997; Kepp et al., 2000; Kim et al., 2003; Barjenbruch and Kopplow, 2003; Valo et al., 2004; Bougrier et al., 2006a, 2006b; Fernandez-Polanco et al., 2008; Perez-Elvira and Fdz-Polanco, 2012; Abelleira-Peraira et al., 2015.

[3] References: Park et al., 2004, Park and Ahn, 2011; Pino-Jelcic et al., 2006; Eskicioglu et al., 2009; Elagroudy and El-Gohary, 2013; Rani et al., 2013; Yeneneh et al., 2015.

[4] References: Dohanyos et al., 2004; Zabranska et al., 2006.

[5] References: Baier and Schmidheiny, 1997; Kopp et al., 1997; Winter, 2002.

[6] References: Barjenbruch and Kopplow, 2003; Onyeche, 2004; Zhang et al., 2012.

[7] References: Weemaes et al., 2000; Yeom et al., 2002; Goel et al., 2003; Sievers et al., 2004; Bougrier et al., 2007; Erden and Filibeli, 2011; Silvestre et al., 2015.

[8] References: Cacho Rivero et al., 2006.

[9] References: Kim et al., 2003; Valo et al., 2004; Zhang et al., 2010.

[10] References: Wang et al., 2013b, 2014b; Zhang et al., 2015; Zahedi et al., 2016.

[11] References: Hasegawa et al., 2000.

WWTPs worldwide. For example, Wessex water employed an ultrasonic system to treat the industrial and domestic mixed sludge in their plant with a population equivalent of 1,200,000 in UK, where it was found that the VS removal was improved by 20% after ultrasonic pretreatment. Several patented technologies regarding ultrasonic pretreatment have been granted, such as Biosonator (Ultrawaves, Germany), Sonix (Sonico, UK), Sonolyzer (Ovivo), smart DMS (Weber Ultrasonics), Iwe.Tec (Germany) and Hielscher (Germany).

3.1.2. Thermal pretreatment

Thermal pretreatment in sludge treatment line is generally carried out at 165–180 °C for 30 min, except that a few cases were performed at 121 °C (see Table 2 and Table S6). The improved TS/VS removal and CH_4 production were in the ranges of 7–32% and 14–90%, respectively, as summarized in Table 2 and Table S6. Thermal pretreatment was able to improve both sludge degradation rate and sludge degradation extent (Batstone et al., 2009). Thermal pretreatment has been applied to the full-scale WWTPs and is the most widely used technology to achieve sludge reduction in sludge treatment line. The first plant with thermal pretreatment (named as Cambi) was operated in 1995 in Hamar, Norway (Kepp et al., 2000). Afterwards, up to 20 other plants also adopted this technology. The thermal pretreatment technology has also been commercialized by several other companies recently to achieve sludge reduction, including Veolia's Biothelys in 2006 with 10 WWTPs, Kruger-Veolia's Exelys in 2010 with 1 WWTP, Sustec's Turbotec in 2011 with 1 pilot plant, Aqualogy's CTH in 2012 with an industrial proto-type, Eliquo's Lysotherm in 2012 with 1 WWTP and Biorefinex in 2013 with 1 WWTP.

3.1.3. Microwave pretreatment

Microwave pretreatment causes sludge disintegration due to microwave heating, which is quite rapid (Park et al., 2004; Yeneneh et al., 2015). Microwave pretreatment is generally conducted at 2450 MHz, 700–1000 W for several minutes (see Table 2 and Table S7). The improved TS/VS removal and CH_4 production were in the ranges of 8–14% and 30–84%, respectively (see Table 2 and Table S7). Till now, microwave pretreatment is only applied at lab scale.

3.1.4. Lysis-thickening centrifuge, stirred ball mill and high pressure homogenization

Lysis-thickening centrifuge is a thickening centrifuge equipped with an additional rotating cutting tool for sludge disintegration, thereby achieving sludge reduction (Zabranska et al., 2006). Lysis-thickening centrifuge has been applied to the full-scale WWTP with a rotation speed of 2250–3140 rpm, resulting in an increased biogas production of 15–26%, as summarized in Table 2 and Table S8.

The stirred ball mill mainly consists of grinding chamber, which is filled with grinding spheres. The sludge disruption is induced by shearing and pressure forces between the spheres (Winter, 2002). The stirred ball mill was applied to the WWTP in 2002. The ball velocity and ball diameter were typically at 6–15 m/s and 0.25–0.35 mm, respectively, while this technology was applied (see Table 2 and Table S8). An increased VS removal of 5% and enhanced biogas production of 10–21% were generally achieved (see Table 2 and Table S8).

High pressure homogenization is another pretreatment technology to achieve sludge reduction in sludge treatment line. This technology has been applied at full scale and has been patented, including Crown (Biogest), MicroSludge (Paradigm Environmental Technology) and Cellruptor (Eosolids). 150–600 bar is usually exploited in high pressure homogenization, resulting in an improved biogas production of 18–64% (see Table 2 and Table S8).

3.1.5. Focused pulsed pretreatment

Focused pulsed (FP) pretreatment employs a high voltage (20–30 kV) and rapid pulse to destruct the bacterial cells and EPS (Choi et al., 2006; Rittmann et al., 2008). This technology has been applied to the sludge treatment line to achieve sludge reduction. Choi et al. (2006) found that the biogas production from FP-treated WAS was 2.5 times higher than that from untreated WAS. Rittmann et al. (2008) exploited FP to treat a mixture of primary sludge and WAS before anaerobic digestion in a full-scale WWTP. It was observed that the TS destruction increased by 40% after FP pretreatment was implemented. The FP-based pretreatment technology has been patented, including OpenCEL and PowerMod.

3.2. Chemical pretreatment

Chemical pretreatment mainly consists of oxidation pretreatment, alkaline pretreatment and FNA pretreatment.

3.2.1. Oxidation pretreatment

Ozonation pretreatment is the most commonly used oxidation pretreatment method in sludge treatment line (Chu et al., 2009). It is generally carried out at 0.05–0.15 g O_3/g TS, resulting in an increased TS/VS removal of 8–28% and an improved CH_4 production of 25–110% (see Table 2 and Table S9). Ozonation pretreatment has been applied to the full-scale WWTP.

3.2.2. Alkaline pretreatment

Alkaline pretreatment is able to break down carbohydrates, lipids and proteins into smaller molecular-weight soluble substances, thereby enhancing the sludge degradability (Zhang et al., 2010). Alkaline pretreatment is typically performed at pH 10 at 120–130 °C with a short contact time (i.e. 30–60 min) or at pH 10 at mesophilic temperature (i.e. 34–36 °C) for several days (see Table 2 and Table S9). The enhanced CH_4 production was in the range of 38–340%. Alkaline pretreatment is only implemented at lab scale till now.

3.2.3. FNA pretreatment

FNA pretreatment is an innovative technology to achieve sludge reduction in sludge treatment line (Wang et al., 2013b, 2014b; Zahedi et al., 2016). It is usually conducted at 1.0–2.5 mg HNO_2-N/L for 5–24 h with an increased CH_4 production of 15–56% (see Table 2 and Table S9). It was reported that FNA pretreatment was able to improve both sludge degradation rate and sludge degradation extent (Wang et al., 2013b, 2014b). FNA pretreatment has only been done in the lab but the pilot-scale tests will be conducted quite soon. It should be highlighted that FNA is a renewable chemical that is able to be produced as a by-product of wastewater treatment via nitritation of anaerobic sludge digestion liquor (Law et al., 2015). After pretreatment, FNA contained in pre-treated WAS would be diluted and rapidly removed in the anaerobic digester, thereby forming a closed-loop pretreatment technology.

FNA has also been combined with heat (55 °C) to further achieve sludge reduction (Wang et al., 2014b). It was reported that the sludge degradation (VS basis) increased from 35% (without pretreatment) to 41% after implementing FNA pretreatment of ~1.0 mg HNO_2-N/L. In contrast, combined FNA and heat pretreatment achieved a sludge degradation of 44% (Wang et al., 2014b).

Zhang et al. (2015) also applied FNA + H_2O_2 to further achieve sludge reduction. The sludge degradations (VS basis) were determined as 30%, 49% and 59%, respectively, for the WAS without pretreatment and the WAS pretreated by FNA of 1.5 mg HNO_2-N/L and FNA + H_2O_2 (1.5 mg HNO_2-N/L + 50 mg H_2O_2/g TS).

3.3. Biological pretreatment

Temperature-phased anaerobic digestion (TPAD) is the most commonly used biological pretreatment approach. It has been developed to increase the efficiency of anaerobic digestion, where a low retention time of thermophilic or hyper thermophilic anaerobic/microaerobic digester (i.e. pretreatment digester) is followed by a long retention time of mesophilic or thermophilic digester (mainly for methanogenesis) (Hasegawa et al., 2000; Bolzonella et al., 2012). The TPAD allows the separation of the initial stages (i.e. hydrolysis, acidogenesis and acetogenesis) of the digestion process from methanogenesis, thereby encouraging the maintenance of desirable operating conditions of separate digesters and enhancing sludge reduction. The temperature in the pretreatment digester is generally at 60–70 °C with a retention time of 9–48 h (Table 2 and Table S10). The enhanced VS removal and improved biogas/CH_4 production were 7–11% and 26–50%, respectively. It was reported that TPAD was only able to improve the sludge degradation rate and had no impact on the sludge degradation extent (Ge et al., 2011). The TPAD has been successfully applied at the pilot plant.

4. Comparison and evaluation of technologies for reducing sludge production

4.1. Technologies applied in wastewater treatment line

The advantages and disadvantages of treatment technologies applied in wastewater treatment line are summarized in Table 3. In general, the sludge settleability could be improved by most of the treatment technologies, including ozonation, ultrasonic treatment (<1000 kJ/kg TSS) (TSS: total suspended solids), high pressure homogenization, thermal treatment, electrical treatment and addition of predators (Elissen et al., 2006; Heinz, 2007; Chu et al., 2009; Feng et al., 2009a). This showed the advantage of the above technologies. However, the free nitrous acid (FNA) treatment technology could not improve sludge settleability (Wang et al., 2013a), and chlorination, ultrasonic treatment (>1000 kJ/kg TSS) and addition of chemical un-couplers would lead to a deteriorated sludge settleability (Feng et al., 2009a; Guo et al., 2014). In terms of cost, FNA treatment technology might be good. However, it should be noted that FNA treatment technology is still in its infancy and only lab-scale tests were conducted (Wang et al., 2013a). Pilot- and full-scale tests are still needed. In contrast, ozonation, ultrasonic treatment and addition of predators have been applied in full-scale WWTPs although technology optimization might still be required to reduce the cost (Neis et al., 2008; Gardoni et al., 2011; Tamis et al., 2011). It should be highlighted that the selection of the treatment technologies would not only depend on the sludge reduction performance, but also on the cost and possible side effects, such as deteriorated sludge settleability and effluent quality. It should also be pointed out that the sludge reduction performance of different technologies could not be directly compared since the sludge reduction results also depend on other factors such as the sludge characteristics in addition to the sludge reduction technologies themselves.

Till now, the uptake of the treatment technologies is still relatively slow in spite of decades of research. Only ozonation, ultrasonic treatment and addition of predators have been applied to the full-scale WWTPs to achieve sludge reduction in wastewater treatment line. However, the other technologies are only tested at lab- or pilot-scale. The rare application of sludge reduction technologies in wastewater treatment line might be due to the high investment/operating costs, which counteract the benefits caused by the reduced sludge production.

4.2. Technologies applied in sludge treatment line

The advantages and disadvantages of pretreatment technologies applied in sludge treatment line are demonstrated in Table 4. Generally, the sludge dewaterability could be enhanced by heat-related pretreatment (i.e. thermal pretreatment, microwave pretreatment and temperature-phased anaerobic digestion) and alkaline pretreatment (Lin et al., 1997; Fernandez-Polanco et al., 2008; Yeneneh et al., 2015). Nevertheless, the sludge dewaterability would be deteriorated by ultrasonic pretreatment (>4400 kJ/kg TS) and ozonation (Feng et al., 2009b; Erden and Filibeli, 2011). Heat-related pretreatment (i.e. thermal pretreatment, microwave pretreatment and temperature-phased anaerobic digestion), together with ozonation and alkaline pretreatment, could also lead to pathogen inactivation (Hong et al., 2006; Carballa et al., 2007; Ge et al., 2011). In contrast, the other technologies did not play a role in pathogen inactivation. In terms of cost, the thermal pretreatment, FNA pretreatment (only lab-scale test was done) and temperature-phased anaerobic digestion showed the advantages, whereas the other pretreatment technologies incurred high cost.

Similar to wastewater treatment line, the sludge reduction performance of different pretreatment technologies in sludge treatment line could not be directly compared as well because of the different sludge characteristics. For instance, the impact of pretreatment technologies on sludge reduction would depend on the initial biodegradability of the sludge, which is in turn dependent on the sludge retention time of the upstream wastewater treatment process. In general, the pretreatment

Table 3
Advantages and disadvantages of sludge reduction technologies applied in wastewater treatment line.

Approaches	Technologies	Technologies	Advantages	Disadvantages
Treatment technologies	Chemical treatment	Ozonation	Improved sludge settleability; process applied at full scale	High investment and operating costs; increase in effluent COD
		Chlorination	Low investment and operating costs compared to ozonation	Formation of by-products; Worsened sludge settleability; increase in effluent COD; only applied at lab scale
		Fenton oxidation	Low investment and operating cost compared to ozonation	Increase in effluent COD; only applied at lab scale
		Free nitrous acid (FNA)	Low investment and operating cost; No effect on sludge settleability and effluent quality	Only applied at lab scale
	Mechanical treatment	Ultrasonic treatment	Low investment costs; improved sludge settleability (<1000 kg/kg TSS); process applied at full scale	Erosion of sonotrodes; high operating costs; Worsened sludge settleability (>1000 kg/kg TSS); increase in effluent COD
		High pressure homogenization	Improved sludge settleability	High investment and operating costs; increase in effluent COD; only applied at pilot scale
	Thermal treatment		Improved sludge settleability	High investment and operating costs; increase in effluent COD; only applied at pilot scale
	Electrical treatment		Improved sludge settleability	High operating cost; increase in effluent COD; only applied at lab scale
Addition of chemical uncouplers	Chemical metabolic uncouplers		Low investment cost	Potential acclimatization of bacteria to uncouplers over long periods; worsened sludge settleability; increase in effluent COD; high cost of uncouplers; only applied at lab scale
Predation of protozoa and metazoa	Addition of predators		Low operating costs; improved sludge settleability; process applied at full scale	Large space required for predation reactor (i.e. high investment cost); difficult to control the quantities of protozoa and metazoa

Table 4
Advantages and disadvantages of sludge reduction technologies applied in sludge treatment line.

Approaches	Technologies	Advantages	Disadvantages
Physical pretreatment	Ultrasonic pretreatment	No odor formation; process applied at full scale	Erosion of sonotrodes; high operating costs; worsened sludge dewaterability (>4400 kJ/kg TS); no pathogen inactivation
	Thermal pretreatment	Pathogen inactivation; improved sludge dewaterability; low operating cost; process applied at full scale	Odor formation; deterioration of equipment
	Microwave pretreatment	Pathogen inactivation; improved sludge dewaterability; less reaction time and lower thermal loss than thermal pretreatment	Odor formation; high investment and operating costs; only applied at lab scale
	Lysis-thickening centrifuge	No odor production; short contact time; process applied at full scale	Deterioration of equipment; high investment and operating costs; no pathogen inactivation
	Stirred ball mill	No odor production; short contact time; process applied at full scale	Deterioration of equipment; high investment and operating costs; no pathogen inactivation
	High pressure homogenization	No odor production; short contact time; process applied at full scale	Deterioration of equipment; high investment and operating costs; no pathogen inactivation
	Focused pulsed pretreatment	No odor formation; process applied at full scale	Erosion of electrode; high operating cost; no pathogen inactivation
Chemical pretreatment	Ozonation	No odor formation; process applied at full scale; pathogen inactivation	Worsened sludge dewaterability; high investment and operating costs;
	Alkaline pretreatment	Improved sludge dewaterability; low investment cost; pathogen inactivation	Corrosion of equipment; high operating cost; only applied at lab scale; potential adverse effect on the subsequent anaerobic digestion
	Free nitrous acid	Low investment and operating costs	Only applied at lab scale; no pathogen inactivation
Biological pretreatment	Temperature-phased anaerobic digestion	Improved sludge dewaterability; pathogen inactivation; low operating cost	High investment costs; odor formation

would be more efficient in achieving sludge reduction when applied to the sludge with a low initial biodegradability (i.e. corresponding to a long sludge retention time) if the other conditions are identical.

Energy consumption is an important factor while choosing a pretreatment technology. Cano et al. (2015) conducted an energy feasibility analysis for the pretreatment technologies. For pretreatment technologies consuming electricity, the energy requirement generally exceeds the electricity produced from the biogas, incurring an energy negative pretreatment. But ultrasonic pretreatment is an exception, which provides an energetically self-sufficient pretreatment. In contrast, thermal pretreatment is generally energetically self sufficient because the thermal energy recovered from biogas is usually in excess in comparison with the WWTP requirement, which is a big advantage of thermal pretreatment. In addition, electricity energy can also be recovered from biogas in the case of thermal pretreatment in the same extent as for pretreatment technologies requiring electricity. With regard to the pretreatment technologies requiring chemical input, the chemicals required could be converted to energy consumption for chemical production. However, the cost for chemical addition rather than for energy consumption should be taken into account for this type of pretreatment. It should be highlighted that energy analysis should be conducted based on the full-scale data rather than on the lab-scale data since the energy inputs of lab-scale equipments may be quite far from the full-scale implementation. For example, ultrasonic pretreatment has shown an energy consumption in the range of 27–118 kWh/(m^3 sludge) based on the lab-scale data (Feng et al., 2009a, 2009b), which far exceeds the generated energy. However, an energy consumption of only 10 kWh/(m^3 sludge) was required for the full-scale ultrasonic pretreatment (Cano et al., 2015). The energy balance would therefore be positive for full-scale plants even if the energy balance is negative using lab-scale data.

Therefore, the pretreatment technologies should be evaluated not only according to the sludge reduction performance (causing reduced sludge disposal cost) but also according to the cost/energy consumption and other factors, such as sludge dewaterability and pathogen inactivation. In general, thermal pretreatment, ultrasonic pretreatment (<4400 kJ/kg TS), FNA pretreatment and temperature-phased anaerobic digestion are promising if the pathogen inactivation is not a big concern (e.g. Class B biosolids are required). But it should be highlighted that FNA pretreatment is only under the lab-scale trial. In contrast, thermal pretreatment and temperature-phased anaerobic digestion are superior to other pretreatment technologies if pathogen inactivation is required (e.g. Class A biosolids are required).

5. Sludge reduction with new treatment process design

5.1. SANI® process

The Sulfate reduction Autotrophic denitrification and Nitrification Integrated (SANI®) process was developed in Hong Kong to reduce sludge production while treating sulfate containing wastewater resulting from seawater toilet flushing (Wang et al., 2009; Lu et al., 2012; Wu et al., 2016). SANI® process consists of three biological reactions (Wang et al., 2009; Lu et al., 2012; Wu et al., 2016). In the first reactor (anaerobic), sulfate-reducing bacteria (SRB) reduce sulfate to sulfide and oxidize organic carbon to CO_2. In the second reactor (anoxic), sulfur-oxidizing bacteria (SOB) oxidize sulfide back to sulfate and reduce nitrate to N_2. In the third reactor (aerobic), autotrophic nitrifiers oxidize ammonia to nitrate. All the functional bacteria (i.e. SRB, SOB and autotrophic nitrifiers) involved in SANI® process are slow growers with low yields. Therefore, SANI® process produces little sludge. SANI® process has been applied at full scale. For instance, Wu et al. (2016) reported that the sludge production rate of SANI® process was 0.19 g TSS/g COD (COD: Chemical Oxygen Demand) in an 800–1000 m^3/d full-scale demonstration plant, which is 60–70% lower in comparison with the conventional activated sludge process performing nitrification-heterotrophic denitrification in Hong Kong. However, it should be noted that the SANI® process is only applicable to the sulfate containing wastewater.

5.2. High-rate activated sludge followed by autotrophic nitrogen removal

High-rate activated sludge (HRAS) followed by autotrophic nitrogen removal (i.e. partial nitritation + anammox) has been proposed as a promising method for maximizing energy recovery from domestic wastewater (Lotti et al., 2015; van Loosdrecht and Brdjanovic, 2014; Laureni et al., 2016; Wang et al., 2016). The wastewater is considered to consist of three forms of substrates, which are particulate, colloidal and soluble substrates. In the HRAS reactor, the particulate and colloidal substrates are removed by bioadsorption and the subsequent solids-liquid separation. The soluble substrate is removed by intracellular storage, biosynthesis and/or biological oxidation. The HRAS reactor can also be replaced with “A stage”, which is mainly based on adsorption. Afterwards, the nitrogen in the effluent of HRAS reactor (or “A stage”) is removed via partial nitritation and anammox. Since most of organic carbon is biodegraded anaerobically (i.e. anaerobic digestion) in this process, the sludge production would be substantially reduced because of the low yield (<0.1 g COD/g COD) of anaerobic microbes. However, this process is still at its infancy and some challenges (e.g. unstable partial nitritation) still exist. Therefore, further studies and full-scale tests are still needed.

5.3. Anaerobic membrane bioreactor followed by autotrophic nitrogen removal

Anaerobic membrane bioreactor (AnMBR) followed by autotrophic nitrogen removal (i.e. partial nitritation + anammox) is also a promising approach for maximizing energy recovery from domestic wastewater (McCarty et al., 2011; Batstone et al., 2013; Solley et al., 2015; Ødegaard, 2016). In the AnMBR, wastewater is treated by anaerobic microbes to convert almost all the biodegradable organic carbon to biogas. The nitrogen is then removed via partial nitriation and anammox. Similar to the high-rate activated sludge coupled with autotrophic nitrogen removal process, the organic carbon is removed anaerobically in this process. Therefore, the sludge production would be significantly reduced due to the low yield (<0.1 g COD/g COD) of anaerobic microbes (Metcalf and Eddy, 2003). Nevertheless, this process is still in the early stage and efforts are still needed to overcome the existing challenges (e.g. unstable partial nitritation and CH_4 recovery in the AnMBR system). As a result, further studies and full-scale tests are required.

6. Conclusions and future perspectives

In this work, the state-of-the-art technologies for reducing sludge production in both wastewater treatment line and sludge treatment line in wastewater treatment plants (WWTPs) were reviewed. The main conclusions are:

- Sludge reduction performances for different technologies are different. But they could not be directly compared due to the different sludge characteristics.
- The technologies should be evaluated not only according to the sludge reduction performance (causing reduced sludge disposal cost) but also according to the cost and other factors, such as sludge settleability, sludge dewaterability and pathogen inactivation
- In wastewater treatment line, free nitrous acid (FNA) technology seems good but it is only under the lab-scale trial. In sludge treatment line, thermal pretreatment, ultrasonic pretreatment (<4400 kJ/kg TS), FNA pretreatment and temperature-phased anaerobic digestion are promising if the pathogen inactivation is not a concern. However, thermal pretreatment and temperature-phased anaerobic digestion are superior to other pretreatment technologies if significant pathogen inactivation is required.
- Some new wastewater treatment process designs including SANI® process, HRAS coupled autotrophic nitrogen removal and AnMBR coupled autotrophic nitrogen removal have a great potential to reduce sludge production. However, SANI® process is only applicable to the sulfate containing wastewater, and HRAS coupled autotrophic nitrogen removal and AnMBR coupled autotrophic nitrogen removal still face some challenges such as unstable partial nitritation.

Although sludge reduction technologies have been extensively investigated, their application in the full-scale WWTPs is still relatively limited. Work in the following areas is necessary in order to better develop sludge reduction technologies:

- While FNA-based sludge reduction technology seems good in wastewater treatment line, pilot and full-scale tests are still needed to further evaluate this technology.
- Different sludge reduction technologies should be applied to the same sludge source in order to accurately compare the sludge reduction performance of different technologies.
- The effect of sludge reduction technologies on the removal of heavy metals (e.g. Cu, Zn, Pb) and organic micropollutants (e.g. PCBs, EDCs) should be evaluated. This is closely related to the achievement of Class A biosolids.
- Challenges for HRAS coupled autotrophic nitrogen removal and AnMBR coupled autotrophic nitrogen removal still need to be overcome. Full-scale tests are still required to evaluate the sludge reduction performance of the two new wastewater treatment processes.

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Appendix A. Supplementary data

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