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A novel approach to realize SANI process in freshwater sewage treatment – Use of wet flue gas desulfurization waste streams as sulfur source

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ABSTRACT

SANI (Sulfate reduction, Autotrophic denitrification and Nitrification Integrated) process has been approved to be a sludge-minimized sewage treatment process in warm and coastal cities with seawater supply. In order to apply this sulfur-based process in inland cold areas, wet flue gas desulfurization (FGD) can be simplified and integrated with SANI process, to provide sulfite as electron carrier for sulfur cycle in sewage treatment. In this study, a lab-scale system of the proposed novel process was developed and run for over 200 days while temperature varied between 30 and 5 °C, fed with synthetic FGD wastewaters and sewage. The sulfite-reducing upflow anaerobic sludge bed (SrUASB) reactor, as the major bioreactor of the system, removed 86.9% of organics while the whole system removed 94% of organics even when water temperature decreased to around 10 °C. The bactericidal effect of sulfite was not observed in the SrUASB reactor, while thiosulfate was found accumulated under psychrophilic conditions. The sludge yield of the SrUASB reactor was determined to be 0.095 kg VSS/kg COD, higher than of sulfate reduction process but still much lower than of conventional activated sludge processes. The dominant microbes in the SrUASB reactor were determined as *Lactococcus* spp. rather than sulfate-reducing bacteria, but sulfite reduction still contributed 85.5% to the organic carbon mineralization in this reactor. Ammonia and nitrate were effectively removed in the aerobic and anoxic filters, respectively. This study confirms the proposed process was promising to achieve sludge-minimized sewage treatment integrating with flue gas desulfurization in inland and cold areas.

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1. Introduction

Current biological sewage treatment processes are mainly built on conversion of organic carbon mineralization by oxygen and oxidized nitrogen such as nitrate, resulting in 234 g sludge per cubic meter of sewage treated as the major byproduct (Tchobanoglous et al., 2002). Excessive sludge treatment and disposal therefore accounts for 30–60% of plant-wide operation costs (Canales et al., 1994; Lotito et al., 2012). Anaerobic sewage treatment via methanogenesis could be an ideal option as its low sludge yield (Lettinga et al., 1980; Seghezzo et al., 1998). However, this option is hardly applicable in simultaneous removal of organics and nitrogen from sewage, though denitrification may be achievable through provision of electron donors by oxidizing methane produced from methanogenesis (Li et al., 2009; Raghoebarsing et al., 2006). To realize anaerobic treatment-based biological nitrogen removal (BNR) towards significant sludge minimization in sewage treatment, we have recently developed a sulfur-based process, named SANI (Sulfate reduction, Autotrophic denitrification and Nitrification Integrated) process (Lau et al., 2006; Lu et al., 2011; Wang et al., 2009). SANI relies up sufficient amount of oxidized sulfurs such as sulfate to act as the electron carrier for anaerobic oxidization of organic carbon into CO_2 and anoxic reduction of nitrate and/or nitrite to nitrogen gas, as shown in Fig. S1 in the Supplementary materials. This novel BNR process can reduce 90% of excess sludge due to very low sludge yields in its three major bioreactions: sulfate reduction, autotrophic denitrification and nitrification, i.e. 0.02 kg VSS/kg COD, 0.01 kg VSS/kg $NO_3^- - N$ and 0.07 kg VSS/kg $NH_4^+ - N$, respectively, while achieving simultaneous removal of organics and nitrogen (Lau et al., 2006; Lu et al., 2011; Wang et al., 2009). The SANI pilot trial has demonstrated that the process can reduce 36% of energy as compared to current BNR processes (Lu et al., 2011). Hong Kong's 50-year practice of seawater toilet flushing (SWTF), which saves 750,000 $m^3$of freshwater daily (Leung et al., 2012), merits the application of SANI process because of sufficient sulfate (500–1000 mg/L) brought from 20 to 30% of seawater through toilet flushing. A full-scale plant for demonstration is, therefore, being constructed in Hong Kong.

In inland areas, low-cost sulfur-rich sources should be available to enable application of SANI in freshwater sewage treatment. High sulfur-laden wastes are extensively produced from wet flue gas desulfurization (FGD) in fossil power stations (Sohn and Kim, 2002; Srivastava and Jozewicz, 2001). If delivering cost of such waste streams to a nearby sewage treatment plant is minimal, SANI technology could be of help in upgrade of existing BNR plants in the inland areas towards energy saving and sludge minimization. In fact, FGD wastes have been anaerobically treated with external hydrogen gas, ethanol, lactic acid or organic-concentrated industrial wastewaters (Ebrahimi, 2005; Philip and Deshusses, 2003; Rao et al., 2007; van Houten et al., 2000), which are known as Bio-FGD processes. Obviously organics in sewage can also act as the electron donor for such process. Sewage has not been adopted in Bio-FGD processes because impurities brought from sewage result in low quality of elemental sulfur as the product. But in SANI process sulfide is fully converted to sulfate, meaning an integration of FGD with SANI process is possible. In order to maximize the benefits from such an integrated process, we further propose to simply the wet FGD process by eliminating enforced oxidation of sulfite to sulfate as well as subsequent $CaSO_4$ precipitation with lime stone, as shown in Fig. 1, since these two steps not only consume energy but also often cause scaling problems in operation (Srivastava and Jozewicz, 2001).

This proposed process is named FGD-SANI process, which is different from previous SANI process. Firstly, changing of the electron carrier from sulfate to sulfite may affect the performance of the anaerobic organic removal. Comparison of the free Gibbs energy between sulfate and sulfite reduction, as shown by Eqs. (1) and (2) (Lens et al., 1998; Muyzer and Stams, 2008), biological sulfite reduction provides more energy for bacterial growth, implying a higher sludge yield than biological sulfate reduction. Since sulfite is an intermediate of sulfate reduction, theoretically the sulfite reduction could be faster than sulfate reduction by sulfur-reducing bacteria (SRB), enabling an efficient co-treatment of FGD wastes and freshwater sewage. Secondly, sulfite is also recognized as an antimicrobial agent against bacterial contamination in wine making (Chang et al., 1997), which may limit the rate of fermentation and could be a negative factor to organic removal rate.

$$\text{Acetate}^- + SO_4^{2-} \rightarrow 2HCO_3^- + HS^- \quad \Delta G^0 = -48(\text{kJ/reaction}) \tag{1}$$

$$\text{Acetate}^- + \frac{4}{3}SO_3^{2-} \rightarrow \frac{5}{3}HCO_3^- + \frac{1}{3}CO_3^{2-} + \frac{4}{3}HS^- \quad \Delta G^0 = -80(\text{kJ/reaction}) \tag{2}$$

Cold weather in inland areas also challenges the application of FGD-SANI, because SRB are generally mesophilic or thermophilic anaerobes, and their activities reduce significantly by low temperature like methanogens (Lettinga et al., 2001). In previous studies, SANI process was only tested in the tropical coastal city, and the performance of organic removal by SRB in low temperature (<15 °C) was not yet investigated. Determination of low temperature impact on biological sulfite reduction becomes essential in this study.

In a preliminary study, organic residues, thiosulfate and sulfide were found in the effluent of the sulfite reduction reactor (Qian et al., 2013), possibly inducing simultaneous

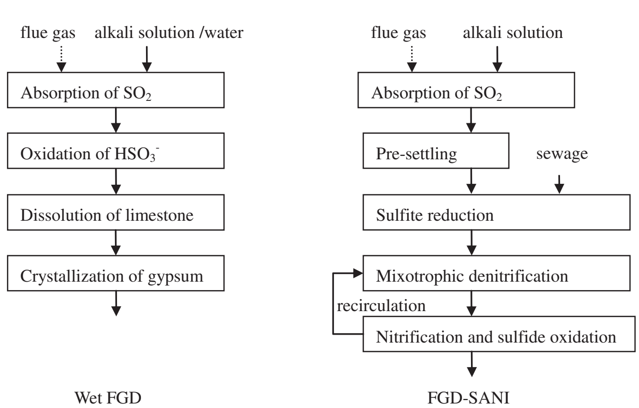

Fig. 1 – Schematic illustrations of wet FGD (Kiil et al., 1998) and the proposed FGD-SANI process.