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Pilot-scale investigation of sludge reduction in aerobic digestion system with endospore-forming bacteria

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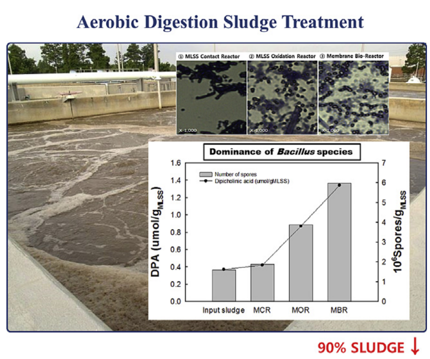
HIGHLIGHTS

- A pilot-scale sludge treatment process was developed and investigated.
- Membrane-based aerobic digestion system could accumulate the sludge.
- 90% of sludge reduction was achieved in sludge treatment process.
- *Bacillus* species was dominant and influenced on the sludge reduction.
- Endospore-forming bacteria-based process could be suitable for sludge reduction.

GRAPHICAL ABSTRACT



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ABSTRACT

A pilot-scale investigation of membrane-based aerobic digestion system dominated by endospore-forming bacteria was evaluated as one of the potential sludge treatment processes (STP). Most of the organic matter in the sludge was removed (90.1%) by the particular bacteria in the STP, which consisted of mixed liquor suspended solid (MLSS) contact reactor (MCR), MLSS oxidation reactor (MOR), and membrane bioreactor (MBR). The sludge was accumulated in the MBR without wasting, and then the effluent in STP was fed into the first step in water resource recovery facility (WRRF). According to the analysis of microbial communities in all reactors, various *Bacillus* species were present in the STP, mainly due to their intrinsic resistance to the extreme conditions. As the surviving *Bacillus* species might consume degraded microorganisms for their growth, these endospore-forming bacteria-based STP could be suitable for the sludge reduction when they operated for a long time.

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1. Introduction

Water Resource Recovery Facilities (WRRFs) using conventional activated sludge processes produce a large quantity of solid by-products as sludge (Vorkamp et al., 2001; Kayser, 2005; Liang et al., 2006). Sludge contains undesirable constituents, including metals (Lee et al., 2005), trace organic contaminants (Nghiem et al., 2009), and pathogenic organisms (Ozores-Hampton and Peach, 2002; Westrell et al., 2004), although several organic and mineral constituents may have fertilizing characteristics (Eriksson, 2001). These undesirable constituents pose sanitary and environmental risks. Worldwide sludge production is anticipated to increase because of several reasons, including the additional treatment processes due to fortified regulation regarding effluent discharge standards of WRRFs (Ryu et al., 2014) and increments of new constructions of WRRFs in developing countries (Buys et al., 2008; Mara, 2013). Consequently, the reduction of sludge production through the various ways, such as installation of anaerobic digesters or pretreatment processes, is emerging and essential. Otherwise, the enormously high cost, with approximately maximum 60% of the total operating cost of a WRRF, is required for sludge treatment and disposal (Zhao and Kugel, 1996; Ge et al., 2013; Wan et al., 2016).

Alternative technologies for directly reducing sludge production on site in WRRFs have been investigated since 1990s (Foladori et al., 2010). These technologies involve decomposition of solid materials using physical, mechanical, chemical, thermal, and biological methods. In the case of physical, mechanical, chemical and thermal processes, the sludge can be disintegrated and increase the solubility by heat (Neyens and Baeyens, 2003), ozone (Sakai et al., 1997; Zhang et al., 2009), ultrasound (Wang et al., 2005; Yang et al., 2015), microwave (Park et al., 2004). Membrane bioreactor technology is also reported to apply in the sludge-return line of WRRFs for sludge reduction (Banu et al., 2009). Degraded microorganisms in sludge can be consumed during anaerobic or aerobic digestion (Huang et al., 2017; Zheng et al., 2017), therefore the prevention of pathogenic infection and sludge stabilization can be achieved. However, these methods are unsuitable for massive environmental clean-ups (*i.e.*, the large-scale of sludge disposal, which requires enormous installation and operating costs). Some chemical reagents used for sludge treatment can cause harmful effects to the environment when these emit to the water environment. Therefore, biological approaches are desirable for the economical and environmentally friendly reduction of sewage sludge. Biological processes for sludge treatment can be divided into four main principles namely cryptic growth with cell lysis, uncoupling metabolism, endogenous metabolism, and microbial predation (Liu and Tay, 2001). The aims of these methods are to increase the disintegration of sludge and/or to decrease microbial growth to minimize sludge production in water or sludge line of WRRFs.

Bacillus species are facultative anaerobes having the ability to grow aerobically or anaerobically (Oliveira et al., 2008). Recently, *Bacillus* species were used for municipal wastewater treatment by bio-augmentation (Yang et al., 2017). The authors reported that *Bacillus* species were contributed to the degradation of chemical oxygen demand (COD) and NH_4^+–N. *Bacillus* species existing in the sludge are not degraded under stressful environment, such as nutrient exhaustion, high temperature, high pressure, extreme pH and high salt concentrations in sludge (Setlow, 1995; Montiel et al., 2001; Asadishad et al., 2014). They can survive by forming endospores, by which other microorganisms cannot survive and release organic matters from inside the cells (Marazioti et al., 2003; Dow et al., 2006). An endospore, which is a surrounded by pore volume, is composed of dipicolinic acids (DPA) linked by Ca^{2+} ions. *Bacillus* species can use the released organic matters as nutrients for growth after they germinate to the vegetative cell in the proper condition (Setlow, 1994).

A novel feasible approach to reduce excess sludge comprises the use of membrane-based aerobic digestion that could be dominated by endospore-forming bacteria. In this study, an aerobic digestion coupled with membrane separation was tested in a pilot-scale investigation with the analysis of microbial community. Endospore-forming bacteria, *Bacillus* species, played a crucial role in the sludge reduction. The dominant mechanisms of *Bacillus* species in this system involved the cryptic growth with cell lysis and suppression of the growth of other microorganisms. In this case, additional processes, such as ozone, ultrasound, or heat, were not necessary for cell lysis to occur. Sludge was degraded by self-oxidation mainly due to nutrient exhaustion in their environment. Also, the maximum growth yield (Y_H) of heterotrophic bacteria was 0.43 ($gCOD_{synthesized}/gCOD_{removed}$) under aerobic condition in the presence of cell lysis-cryptic growth (Obernosterer and Herndl, 1995), but the Y_H of *Bacillus* species was 0.20 ($gCOD_{synthesized}/gCOD_{removed}$) (Babel and van Verseveld, 1987). Therefore, dominance of endospore-forming bacteria can affect sludge reduction. A pilot-scale plant was operated for a year to evaluate the efficiency of *Bacillus* species for the sludge reduction, and the results were discussed in this study. This approach would be helpful in improving the sludge treatment technology for zero emission of excess sludge in WRRFs.

2. Materials and methods

2.1. Process configuration

The influent wastewater of 500 $m^3\ d^{-1}$ was treated in a full-scale WRRF, and they have an approximately 5 $m^3\ d^{-1}$ of sludge production (Fig. 1). The WRRF consisted of an anaerobic reactor (47 m^3), intermittent aeration reactors (73 m^3), and a sedimentation basin (88 m^3). Averaged hydraulic retention time (HRT) and the sludge retention time (SRT) were 6.5 h and 19.3 days, respectively. The influent was introduced from the flow adjustment tank to the anaerobic reactor that could remove the organic matters and release phosphorus. In the intermittent tanks, nitrification and denitrification reactions occurred and the phosphorus was removed by excessive intake of microorganisms in the wastewater (Tsuneda et al., 2006). In the sedimentation tank, precipitated

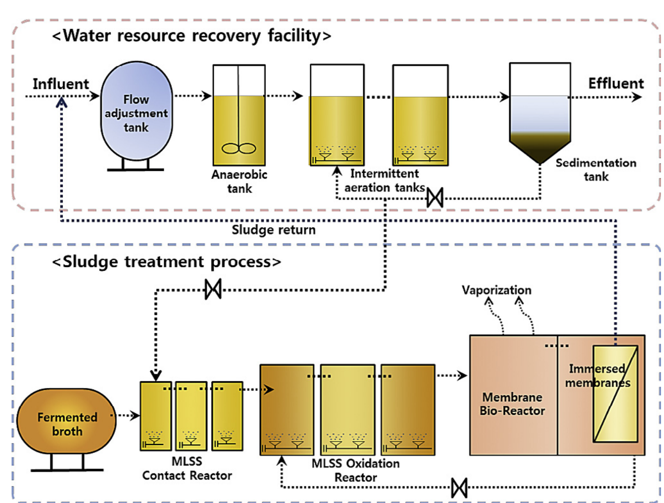

Fig. 1. Schematic diagram of the advanced wastewater treatment processes in a full-scale WRRF, followed by sludge treatment process (STP) tested in this study.