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Review

Sludge cycling between aerobic, anoxic and anaerobic regimes to reduce sludge production during wastewater treatment: Performance, mechanisms, and implications

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HIGHLIGHTS

- Sludge yield (Y) reduction via exposure to alternating redox conditions is reviewed.
- SRT affects sludge yield, but is not the sole important factor in sludge reduction.
- ORP, temperature, sludge recycle ratio and loading mode are important factors.
- Reduced 'Y' but better organic removal and sludge settleability may be achieved.
- The impact of this approach on sludge odour and dewaterability remains unclear.

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ABSTRACT

Alternate cycling of sludge in aerobic, anoxic, and anaerobic regimes is a promising strategy that can reduce the sludge yield of conventional activated sludge (CAS) by up to 50% with potentially lower capital and operating cost than physical- and/or chemical-based sludge minimisation techniques. The mechanisms responsible for reducing sludge yield include alterations to cellular metabolism and feeding behaviour (metabolic uncoupling, feasting/fasting, and endogenous decay), biological floc destruction, and predation on bacteria by higher organisms. Though discrepancies across various studies are recognisable, it is apparent that sludge retention time, oxygen-reduction potential of the anaerobic tank, temperature, sludge return ratio and loading mode are relevant to sludge minimisation by sludge cycling approaches. The impact of sludge minimisation on CAS operation (e.g., organics and nutrient removal efficiency and sludge settleability) is highlighted, and key areas requiring further research are also identified.

1. Introduction

Biological treatment is the most widely used approach to managing domestic and industrial wastewaters. It involves the transformation of dissolved and suspended organic matters to gases and settleable biomass or sludge by a consortium of micro-organisms. While biological treatment offers high organic removal efficiency, it also entails significant production of sludge, which contains active (live) and inactive (dead) micro-organisms and must be treated prior to disposal to prevent adverse impact on public health and the environment. Sludge treatment in typical wastewater treatment plants (WWTP) includes thickening, anaerobic or aerobic digestion, and dewatering to decrease sludge volume, odour, pathogenicity, and vector attraction (Tchobanoglus et al., 2003). However, even after treatment, the amount of remaining sludge in dry mass is still significant, thereby representing a major fraction of the total operating cost during wastewater treatment.

The increase in wastewater treatment coverage in response to sanitary improvement has consequently increased the production of sludge that requires management and disposal. In 2005, the EU generated 10 million tonnes of dry sludge (Fytili and Zabaniotou, 2008). In 2010, China generated 11.2 million tonnes of dry sludge (Foladori et al., 2010). In Australia, dry sludge

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production from wastewater treatment increased by about 3% each year from 0.30 million tonnes in 2010 to 0.33 million tonnes in 2013 (NWC, 2013). Thus, the production of excess sludge from biological treatment is one of the most vexing problems for WWTP operation and necessitates effective management strategies.

Further issues arise during the disposal of the treated sludge. In the past, sludge was commonly disposed through landfilling, incineration, and agricultural re-use. Landfilling has become increasingly impractical due to the high cost of land acquisition and tightening of restrictions on landfill operation activities (Wei et al., 2003). Incineration decreases the volume of solids by up to 95%. However, it requires expensive machinery, consumes non-renewable resources, and has negative public impression (Tchobanoglus et al., 2003). The re-use of sludge as fertiliser or soil conditioner is an appealing option because it adds economic value to waste. However, this practice often requires long distance transport of the treated sludge to the end users. In addition, sludge may contain heavy metals (Tchobanoglus et al., 2003) and trace organic chemicals that are potentially toxic (Clarke and Smith, 2011). Thus, there is a risk of circulation and accumulation of harmful substances in the environment and food products. Therefore, sludge minimisation is generally preferred over sludge treatment as it cascades to a decrease in sludge handling, stabilization, transportation, and disposal expenses.

Considerable research efforts have been devoted to sludge production minimisation during biological wastewater treatment. Sludge minimisation could be achieved via several techniques, namely, control of operating parameters, disintegration of return activated sludge (RAS) by physical, thermal, or advanced oxidation processes (Chu et al., 2009; Foladori et al., 2010; Liu, 2003; Neyens and Baeyens, 2003; Pilli et al., 2011), addition of chemicals that disrupt biomass growth (Liu, 2003), and alternating redox conditions (aerobic, anoxic, and anaerobic sludge cycling regimes) (Foladori et al., 2010). Controlling parameters such as increasing sludge retention time (SRT) and dissolved oxygen (DO) concentration, can only yield marginal improvement but may increase plant operation costs (Wei et al., 2003). The disintegration of sludge significantly reduces sludge production, but requires high capital investment and on-going maintenance (Foladori et al., 2010). In addition, the use of chemicals or advanced oxidation processes can introduce potential contaminants to the sludge and effluent streams (Mahmood and Elliott, 2006). Thus, sludge cycling between different redox conditions is arguably the most benign and cost-effective approach to minimise sludge yield. This approach is not new and was first explored by Westgarth et al. (1964), who inserted an anaerobic tank in the return sludge line that resulted in a 50% decrease in sludge production. Chudoba et al. (1992) made some process modifications to this approach and coined the term "oxic-settling-anaerobic" (OSA). Thus, the generic OSA process can be defined as the recirculation of waste activated sludge (WAS) between (a) an external anoxic or anaerobic and substrate-deficient chamber, and (b) the aerobic and substrate-rich main bioreactor.

Recent research has demonstrated that OSA could reduce sludge yield by up to 55% (Chen et al., 2003; Saby et al., 2003). The OSA process is simple and thus it can be readily retrofitted to existing plants as well as implemented in new designs. However, despite its immense potential, the present level of understanding of OSA is still limited. There is a marked contention in the literature on the mechanisms underlying biological sludge reduction (Chen et al., 2003; Chudoba et al., 1992) and influence of key operating parameters including SRT, oxidation reduction potential (ORP), temperature and solid interchange rate and frequency on the performance of OSA and similar approaches.

Excellent reviews on conventional sludge minimisation approaches (Guo et al., 2013; Liu and Tay, 2001; Mahmood and Elliott, 2006; Wei et al., 2003), and specific sludge minimisation techniques, such as thermal treatment (Neyens and Baeyens, 2003), ultrasonication (Pilli et al., 2011), and conventional and advanced chemical oxidation (Chu et al. 2009; Liu, 2003), are available in the literature. However, none has focused on biological sludge minimisation by OSA and similar sludge cycling schemes. Thus, this paper aims to provide an in-depth discussion on systems that perform aerobic/anaerobic/anoxic cycling by treating RAS in an external oxygen-deficient tank(s). Differences in system configurations and their impact is discussed and related to the degree of sludge minimisation. The discussion focuses on possible mechanisms behind the observed reduction of sludge yield, as well as the pertinent operating parameters that influence sludge minimisation. The impact of the external oxygen-deficient tank on the performance of biological treatment (e.g., chemical oxygen demand (COD) and nutrient removal efficiency) is also systematically assessed. This paper provides a critical analysis of the available literature, identifies gaps in knowledge and highlights areas for future research.

2. Sludge minimisation: alternating redox conditions vs. other methods

2.1. Overview of various sludge minimisation techniques

During wastewater treatment processes, primary sludge from the primary settling tank easily decomposes in the sludge treatment units. Secondary or waste sludge generated by biological treatment can also be digested but is usually produced in excessive amounts. OSA and other sludge minimisation techniques that are discussed in this review (Table 1) are implemented in the wastewater treatment process, i.e., in the main bioreactor or the 'bioreactor-settling tank-RAS' loop. A simple technique to reduce sludge yield is to manipulate key operating parameters (including SRT and DO) during wastewater treatment. Long SRT and high DO concentration decrease biomass growth but require excessive aeration (Wei et al., 2003) (Table 1). Another technique is to disintegrate RAS before it is re-routed back to the main bioreactor. Sludge can be broken up using a number of methods including thermal treatment (heating sludge at 40–180 °C) (Camacho et al., 2005; Canales et al., 1994; Neyens and Baeyens, 2003), thermochemical treatment (combination of heating and adding acid or base) (Do et al., 2009; Neyens and Baeyens, 2003; Rocher et al., 2001; Uan et al., 2013), ultrasonication (the application of low frequency ultrasonic waves, e.g., 25 kHz or lower) (Vaxelaire et al., 2008; Zhang et al., 2007), ozonation (the application of ozone as oxidising agent) (Ahn et al., 2002; Kamiya and Hirotsuji, 1998; Yasui et al., 1996), and chlorination (the application of chlorine as oxidising agent) (Chen et al., 2001b; Saby et al., 2002; Takdastan and Eslami, 2013). The disintegration of sludge by either physical or chemical methods amplifies cell lysis, and the continuous recirculation of lysates results in a net loss of biomass (a process called cryptic growth, which is discussed in more detail in Section 4.1). Certain sludge disintegration methods also improve sludge settling and/or dewatering (Table 1), but their common disadvantage is the high capital investment and maintenance cost of additional treatment units. Moreover, advanced oxidation processes such as ozonation or chlorination may result in the production of toxic by-products (Mahmood and Elliott, 2006). Sludge minimisation can also be achieved through the addition of metabolic uncouplers. Energy uncoupling is the detachment of catabolism from anabolism that cuts off energy for cellular propagation (discussed in more detail in Section 4.4). Various halogenated phenols (Low and Chase, 1998; Yang et al., 2003) and 3,3′,4′,5-tetrachlorosalicylanilide (TCS) (Chen et al., 2002) interfere with metabolic processes and inhibit biomass growth. Nevertheless, the toxicity of phenolic compounds is well known (Clarke