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Review

Is denitrifying anaerobic methane oxidation-centered technologies a solution for the sustainable operation of wastewater treatment Plants?

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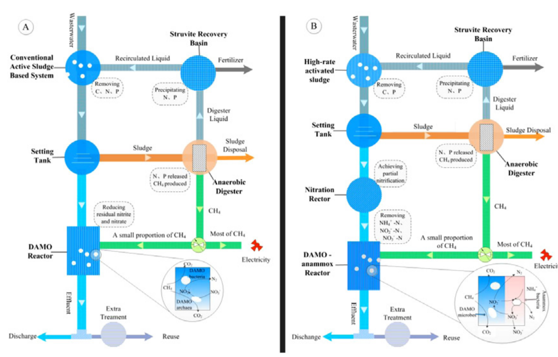
HIGHLIGHTS

- Denitrifying anaerobic methane oxidation (DAMO) process is systematically summarized.
- DAMO process is important to the carbon and nitrogen cycling.
- DAMO-centered technologies may be a solution for sustainable operation of WWTPs.

GRAPHICAL ABSTRACT



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ABSTRACT

With the world's increasing energy crisis, society is growingly considered that the operation of wastewater treatment plants (WWTPs) should be shifted in sustainable paradigms with low energy input, or energy-neutral, or even energy output. There is a lack of critical thinking on whether and how new paradigms can be implemented in WWTPs based on the conventional process. The denitrifying anaerobic methane oxidation (DAMO) process, which uses methane and nitrate (or nitrite) as electron donor and acceptor, respectively, has recently been discovered. Based on critical analyses of this process, DAMO-centered technologies can be considered as a solution for sustainable operation of WWTPs. In this review, a possible strategy with DAMO-centered technologies was outlined and illustrated how this applies for the existing WWTPs energy-saving and newly designed WWTPs energy-neutral (or even energy-producing) towards sustainable operations.

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1. Introduction

As a response to the massive amounts of discharged wastewater caused by rapid urbanization and industrialization, wastewater treatment plants (WWTPs) play an important role in the protection of environment, especially natural water bodies, via a series of biomass mediated processes such as assimilation, dissimilation, nitrification, and denitrification (Chen et al., 2016; Zhao et al., 2015a; Chen et al., 2013, 2015). Treating wastewater to environmentally acceptable level is usually costly, requiring considerable energy input (electricity consumption for domestic wastewater treatment alone accounts for ~3% of global electricity consumption). In China, ￥0.6–0.8 (￥10 [10 yuan] = US$1.40) is generally needed to clean one cubic meter of domestic wastewater, which is much higher for industrial wastewater treatment. Due to the huge quantity of wastewater treated annually (more than 38 billion cubic meters in China alone (Ministry of Environmental Protect, 2014), any improvement in the operation of WWTPs is likely to significant economic and ecological outcomes.

With the growing global population, WWTPs are now faced with new challenges. The growth in the world's population inevitably produces an increasing amount of wastewater, posing risks in relation to overloading environmental capacity if the existing water-quality standards are maintained. To eliminate this threat, stricter water-quality standards are enforced by many countries, especially those countries, such as China, with vulnerable self-purifying natural water bodies. To meet the stricter quality standards, it is generally thought that treating wastewater will require more energy input. Nevertheless, large amounts of energy and resources in wastewater or municipal sludge including carbon, nitrogen, and phosphorus, are currently being squandered. The recovery of energy and resources from WWTPs could either offset part of the cost or make WWTPs energy-neutral or even energy-producing (Luo et al., 2011). This aspect is becoming even more important as the world's increasing population needs more energy and resources, with WWTPs increasingly considered as facilities for energy recovery rather than merely for waste removal (Wang et al., 2009, 2014). The paradox from a quickly increasing human population is pushing forward new improvements for future operation of WWTPs.

Efforts have been dedicated to designing new paradigms for WWTPs to recovery energy and resources as much as possible (Chen et al., 2015; Li et al., 2014), but enabling concurrent maximum energy recovery and desirable pollutant removal remain a huge challenge. Moreover, most of the proposed paradigms present completely new concepts with integrated advanced technologies (Li et al., 2008; Wang et al., 2008; Zhao et al., 2016; Zeng et al., 2013; Chen et al., 2014a,b,c), however, the conventional "activated sludge process" is still (and will be) at the heart of municipal wastewater treatment technology both now and in the next few decades (Hülsen et al., 2016). This makes the proposed paradigms impracticable in the improving the numerous existing WWTPs which use the conventional "activated sludge process", leaving a gap between WWTPs' current and future operations. To date, there is a lack of critical thinking on whether and how new paradigms are to be implemented in WWTPs based on the conventional "activated sludge process".

The denitrifying anaerobic methane oxidation (DAMO) process, which does not require expensive electron donors such as acetate, methanol, and ethanol, has recently been found in both natural habitats and engineered systems (Raghoebarsing et al., 2006; Shi et al., 2013). In 2006 Raghoebarsing et al. (2006) cultivated an enrichment culture from a Dutch canal sediment and detected the concurrent consumption of methane, nitrite and nitrate as well as the emission of dinitrogen gas. Further investigation revealed that the amount of nitrite and nitrate consumed was equal to the dinitrogen gas produced, which, for the first time, demonstrated the existence of anaerobic methane oxidation (AMO) coupled to denitrification. Luesken et al. (2011b) found the DAMO process present in wastewater sludge enrichment cultures from ten selected WWTPs in Netherlands by using specific pmoA primers and fluorescence oligonucleotide probes. The following equations show the reactions of the DAMO process with nitrate (or nitrite) as the oxidant:

$$CH_4 + 4NO_3^- \rightarrow CO_2 + 4NO_2^- + 2H_2O \qquad (\Delta G^\circ = -503\ \text{kJ mol}/CH_4) \quad (1)$$

$$3CH_4 + 8NO_2^- + 8H^+ \rightarrow 3CO_2 + 4N_2 + 10H_2O \qquad (\Delta G^\circ = -928\ \text{kJ mol}/CH_4) \quad (2)$$

The findings on the DAMO process expand our understanding in terms of methane oxidation and may make an important contribution to the WWTPs' operation. It is generally considered that the two main issues faced by WWTPs are: 1) shortage of carbon sources in influent wastewater and 2) emission of greenhouse gas. Thus, if part of the methane produced from the anaerobic digestion of sludge is used to reduce nitrate or nitrite oxidized by denitrifiers, both the nitrogen level in effluent of WWTPs and the greenhouse gas emission from WWTPs will decrease. It is known that WWTPs are highly engineered systems, giving engineers opportunities to develop DAMO based strategies.

In this review, we summarize the critical outcomes arising from the research on the DAMO process. Based on critical analysis, we outline one possible strategy for applying the emerging DAMO-centered technologies to WWTPs, illustrate how this strategy would make the existing WWTPs energy-saving and newly designed WWTPs energy-neutral or even energy-producing, and discuss future efforts to be made for realizing such sustainable operations.