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## 論　文　の　要　旨

## Abstract of thesis


Anaerobic digestion (AD) has been widely applied in wastewater treatment plants (WWTPs) to simultaneously decompose organic compounds and recover energy (mainly as $CH_4$) from sewage sludge annually produced with increasing amount. Although sludge volume can be reduced to some extent, AD of sludge is still facing challenges due to its characteristics like high water content and poor dewaterability of the digestate, and difficulty in its posttreatment with high nitrogen (N) and phosphorus (P) levels. As for the AD system, high biogas quality, efficient nutrients (N and P) recovery, and better digestate dewaterability are the major considerations for the sustainable management of AD-based sewage sludge treatment. This research for the first time attempted the combination of biogas recirculation with chemical addition ($MgCl_2$ or $FeCl_3$) in one AD reactor through both batch- and semi-continuous AD experiments.

This dissertation is divided into 6 chapters. In Chapter 1, the author introduced the research background and literature review. In this chapter, the author discussed the existing problems of sewage sludge treatment, including those from AD process, nutrients recovery, and sludge conditioning/ dewatering. Specifically, the author addressed the great potentials of biogas recirculation together with chemical ($Mg^{2+}$/$Fe^{3+}$) addition, and then arrived at the objectives and framework of this research. In Chapter 2, the author investigated the effect of biogas recirculation coupling with $MgCl_2$ addition on the batch AD of sewage sludge. Results show that $CH_4$ content could be increased to 86% during 17 days' batch AD, attributable to the dissolution of $CO_2$, during which the bioavailable P fraction in sludge was not affected. The $MgCl_2$ addition at an Mg:$P_{ortho}$ molar ratio of 1:1 conserved 87% of

soluble P and 19% of ammonia N, mainly in the form of struvite in the solid phase of digestate. The dewaterability of sludge digestate was enhanced by 37% under the test combination of $MgCl_2$ addition with biogas recirculation. A strong correlation between extracellular polymeric substances (EPS) and sludge dewaterability was also found, and a shorter hydraulic retention time (HRT) with biogas recirculation (17 days) is proposed to enhance methane content and improve sludge dewaterability. In Chapter 3, the author researched the effect of biogas recirculation coupling with $FeCl_3$ addition on the batch AD of sewage sludge. Results show that $FeCl_3$ addition at a dosage > 600 mg-Fe/L (49 mg-Fe/g-TS) enhanced methane content to 88% during batch AD with biogas recirculation. An $FeCl_3$ addition of 900 mg-Fe/L did not affect the methane yield during 30 days' batch AD but significantly reduced the biogas rate constant ($k$) and maximum methane production rate ($\mu$) estimated from the first-order kinetic model and modified Gompertz model. The formation of carbonate precipitates might be the reason of the further increased methane content with increasing dosage of $FeCl_3$. It was found that $FeCl_3$ addition at an $Fe:P_{ortho}$ molar ratio of 1.5:1 (900 mg-Fe/L) achieved 99% conservation of P in the solid phase of digestate. The sludge dewaterability and settleability were enhanced by 79% and 56% when $FeCl_3$ addition was conducted at 900 mg-Fe/L (68 mg-Fe/g-TS) together with biogas recirculation during the batch AD test. In Chapter 4, the author established two semi-continuous AD systems to compare and manifest the effects of the combination of biogas recirculation and $Mg^{2+}/Fe^{3+}$ addition. $MgCl_2$ addition almost did not contribute to P conservation, while $FeCl_3$ addition achieved 97% of P conservation in the solid phase of the digestate. The sludge dewaterability was enhanced by 76% and 94% under tested $MgCl_2$ (12 mg-Mg/g-TS) and $FeCl_3$ (19 mg-Fe/g-TS) addition conditions, respectively. In Chapter 5, the author analyzed the mechanisms and benefits involved in the newly-developed AD system. The changes in archaeal and eubacterial communities revealed that biogas recirculation enhanced the relative abundance of both acetoclastic and hydrogenotrophic methanogens, contributing to the increased methane yield and methane content in biogas. Finally, in Chapter 6, the author summarized the major conclusions, and proposed the future research directions.

## 審　査　の　要　旨
## Abstract of assessment result

This research trialed the combination of biogas recirculation with chemical addition ($MgCl_2$ or $FeCl_3$) in one AD reactor for both batch- and semi-continuous AD of sewage sludge. This newly developed AD system achieved biogas content to 83-88%, P and N resources conservation (up to 99% of P and 69% of N) and enhanced sludge dewaterability by 37-94% simultaneously, depending on the sludge characteristics and operation conditions. Comparison was also conducted on the performance of the AD system between divalent $Mg^{2+}$ and trivalent $Fe^{3+}$ addition. The novel AD system established in this study demonstrated the possibility to simplify the sludge treatment facilities in WWTPs, which is potentially to realize simultaneous biogas upgrading, P conservation and sludge conditioning in one AD reactor system. Before its practical application, more research and discussion are demanding on the mechanisms involved in this novel AD system, and the different changes of microbial communities during batch- and semi-continuous AD operation. The optimization of the whole AD system is also necessary in the context of the real WWTPs.

The final examination committee conducted a meeting as a final examination on 18 July, 2019. The applicant provided an overview of the dissertation, addressed questions and comments raised during Q & A session. All of the committee members reached a final decision that the applicant has passed the final examination.

Therefore, the final examination committee approved that the applicant is qualified to be awarded the degree of Doctor of Philosophy in Environmental Studies.