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Carbon flow, energy metabolic intensity and metagenomic characteristics of a Fe (III)-enhanced anerobic digestion system during treating swine wastewater

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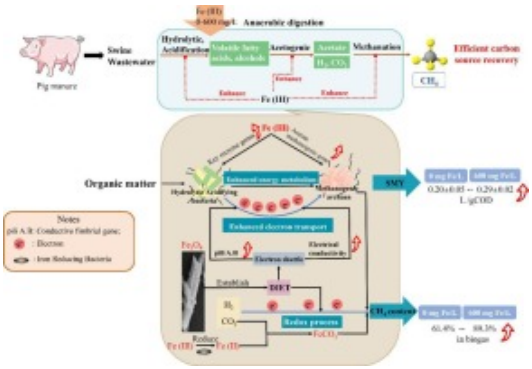
Highlights

- The maximum methane concentration of biogas recovery reached 89.3±2.0%.
- The maximum specific methane yield reached 0.29±0.02 L/g COD.
- Fe compounds acted as an electron shuttle to establish the DIET pathway.
- Fe(III) enhanced the energy metabolism and electron transport of microorganisms.
- Fe(III) enriched the genes of characteristic enzymes of acid and methane production.

Abstract

Deep treatment and bioenergy recovery of swine wastewater (SW) are beneficial for constructing a low-carbon footprint and resource-recycling society. In this study, Fe (III) addition from 0 to 600 mg/L significantly increased the methane (CH_4) content of the recovered biogas from 61.4±2.0 to 89.3±2.0% during SW treatment in an anaerobic membrane digestion system. The specific methane yields (SMY) also increased significantly from 0.20±0.05 to 0.29±0.02 L/g COD. Fe (III) and its bio-transformed products which participated in establishing direct interspecific electron transfer (DIET), upregulated the abundance of e-pili and Nicotinamide adenine dinucleotide (NADH), enriched electroactive bacteria. The increase in cellular adenosine triphosphate (cATP) from 6583 to 14,518 ng/gVSS and electron transport system (ETS) from 1468 to 1968 mg/(g·h) promoted the intensity of energy flow and electron flow during anaerobic digestion of SW. Moreover, Fe (III) promoted the hydrolysis and acidification of organic matters, and strengthened the acetoacetic methanogenesis pathway. This study established an approach for harvesting high quality bioenergy from SW and revealed the effects and mechanisms from the view of carbon flow, energy metabolic intensity and metagenomics.

Graphical abstract



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Introduction

With the continued economic development and population growth, the demand for pork has increased. However, this has also led to increased pollution from pig farming. Studies have shown that China generates approximately 11 million tons of SW annually, making it one of the main sources of agricultural pollution (Che et al., 2017). Generally, SW contains pollutants such as 2000–30,000 mg COD/L, 110–1650 mg NH_4^+-N/L, 200–2055 mg TN/L, and 100–620 mg TP/L (Cheng et al., 2019). Anaerobic digestion (AD) technology, which converts organics into CH_4 through hydrolysis, acidification, and methanogenesis, is a mature organic pollutant-to-energy conversion technology (Lourinho et al., 2020). Against the backdrop of the dual pressure from energy demands and livestock farming pollution, resource utilization and energy conversion of livestock waste are crucial pathways for achieving carbon neutrality, and peaking emission goals. However, AD is susceptible to the impact of organic load and the toxic effect of volatile short-chain fatty acids (VFAs) accumulation, resulting in the reduction of CH_4 recovery efficiency and the inhibition of AD system (Zhang et al., 2020).

Iron (Fe) is a microelement necessary for microbial synthesis and catabolism in AD. Studies have shown that iron compounds enhance microbial electron exchange, subsequently promoting CH_4 recovery (Haidong Zhou et al., 2020). For example, Fe and its compounds have been found to enhance the DIET pathway between microorganisms and influence the synthesis and degradation of the metabolic patterns of microorganisms in AD systems (Li et al., 2019). Previous research has demonstrated that magnetite, as an electron acceptor, stimulates the synthesis of ATP in Fe (III)-reducing bacteria and enhances energy metabolism within the system (Li et al., 2021). Zhao et al. (2018) also demonstrated that 10g/L of zero-valent iron and Fe_3O_4 increased CH_4 production by 50.7% and 40.8%, respectively. Cai et al. (2018) confirmed that 10–500mg Fe^{2+}/L promoted the AD process, while 50mg Fe^{2+}/L has the best effect on the CH_4 production, and a small amount of iron cannot achieve this effect.

Anaerobic membrane bioreactors (AnMBRs) can retain microorganisms and large particles within the reactor (Dagnew and Parker, 2021). Zhen et al. (2019) demonstrated that functional microbial communities which are involved in anaerobic digestion could be retained by the AnMBR membrane components. Zhang et al. (2021) used an AnMBR to perform anaerobic fermentation with a CH_4 conversion efficiency of 78.52%. In addition, the filtration effect of AnMBR membrane components can also trap Fe compound in the reactor and continue to act on microorganisms. Thus, the purpose of enhancing the utilization rate of Fe in AD and promoting the intensity of microbial energy metabolism can be achieved. The microbial metabolic rate in an AD system is limited by the maximum amount of ATP available in the reaction system, the growth of methanogens requires sufficient ATP to drive the synthesis of cells, catabolic processes, and other biological activities (Patón and Rodríguez, 2019; Zhao et al., 2020). However, few studies have discussed the intermediate processes of energy metabolism that are affected by ATP in AD process in detail. The effects of Fe, in combination with an AnMBR, on carbon flow, energy flow direction and electron flow direction in AD process has not been systematically studied. At the microscopic level, the effects of Fe on microbial interactions and changes in gene expression related to methane production pathways are worthy of further discussion.

This study aims to reveal the changes in the carbon flow direction of chemical oxygen demand (COD), microbial energy metabolic intensity, and the redox electron transfer process in an Fe (III)-enhanced AnMBR system during treating SW. In addition, the variation in the abundance of key microbial communities and multi-response interactions based on metagenomes were also discussed. Finally, the regulatory effect and potential mechanisms of Fe (III) on anaerobic CH_4 production in the anaerobic membrane digestion system are systematically described.

Section snippets

Design and operation of the reaction system

The seeding sludge was obtained from anaerobic fermentation unit at a food waste treatment plant in Xiamen, China. Peristaltic pumps were used to feed SW to the continuous stirred tank reactor (CSTR, 2L) unit and subsequently pump the mixed liquor to the AnMBR (4L) (Fig.S1). The membrane in the AnMBR was composed of polyvinyl chloride with a mean pore size of 0.2μm, and an effective

filtration area of 0.06 m^2. A pump was added between the CSTR and AnMBR, allowing the mixed liquor in the …

Methane recovery performance and material flow direction under different OLR(Phase I-III)

The SW treatment performance at each stage is shown in Fig. 1. During Phases I-III, the OLR increased from 0.54 to 0.90 g COD/$L_{reactor}$/day by shortening the Hydraulic retention time (Hydraulic retention time, HRT=5, 4, 3d, Fig. 1a). The average CH_4 production of the reaction system was 0.18 L/L/d in Phase I (HRT=5d), and 0.30 L/L/d in Phase III (HRT=3d). The SMY of Phases I, II, and III were relatively stable at 0.20±0.05 L/g COD (Fig. 1b). In addition, the CH_4 and CO_2 contents in the …

Conclusion

In the system where the CSTR-AnMBR processes SW, when the Fe (III) concentration increases from 0 to 600 mg/L, the CH_4 content of biogas increases from 61.4 to 89.3%, and the SMY reached 0.29±0.02 L/g COD. The addition of Fe (III) enhanced energy and electronic exchange between microorganisms, and improving the efficiency of energy recovery. Fe (III) assisted in the establishment of the DIET pathway in the AD system, improving electron transfer between microorganisms, and strengthens the …

CRediT authorship contribution statement

Hongyu Xie: Writing – review & editing, Writing – original draft, Visualization, Data curation, Conceptualization. **Yuzheng Wang:** Visualization, Methodology, Data curation. **Yuqi Chen:** Writing – review & editing, Visualization, Validation, Methodology. **Yong Hu:** Writing – review & editing, Validation, Formal analysis. **Rasheed Adeleke:** Validation, Methodology. **Linda Obi:** Validation, Methodology. **Yuanpeng Wang:** Methodology, Formal analysis. **Wenzhi Cao:** Validation, Methodology. **Jih-Gaw Lin:** …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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