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Enhanced granulation and methane recovery at low load by downflow sludge circulation in anaerobic treatment of domestic wastewater

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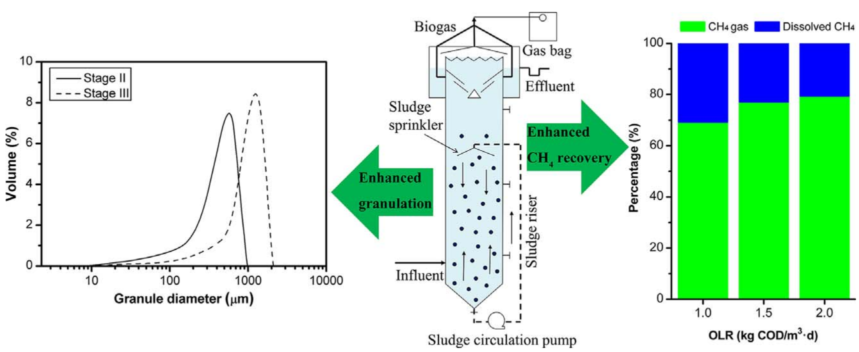
GRAPHICAL ABSTRACT



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ABSTRACT

The effects of downflow sludge circulation on granulation and methane recovery at low load were investigated for domestic wastewater treatment in a modified anaerobic reactor. Compared with conventional upflow anaerobic reactors, enhanced granulation with shortened start-up time was achieved and stable granules were successfully cultivated only after 58 days operations. The introduction of downflow sludge circulation resulted in reverse wastewater-sludge flow and uniform sludge distribution in the reaction zone, which contributed to enhanced wastewater-sludge mass transfer and satisfactory performance with a high soluble chemical oxygen demand (SCOD) removal efficiency of 94.8% at hydraulic retention time (HRT) 6 h. Besides, enhanced liquid-to-gas mass transfer caused a lower dissolved CH_4 saturation index of 1.11 and a higher CH_4 recovery efficiency of 79.48% at HRT 6 h. High throughput sequencing revealed a distinct shift of microbial community during start-up period from Proteobacteria to Bacteroidetes and Chloroflexi in the existence of downflow sludge circulation.

1. Introduction

In the past few decades, with the rapid economic development and population growth, domestic wastewater emissions increased dramatically. A large number of untreated domestic wastewater was discharged into rivers and lakes, deteriorating the surface water and groundwater quality, triggering a series of environmental concerns and potential threats (Gao et al., 2017). To cope with these alarming issues, an efficient, economical and workable process of domestic wastewater treatment was urgently needed. Anaerobic treatment of wastewater as an advanced technology attracted increasing attention and played an important role in environmental protection, sanitation improvement and

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resources recovery (Deng et al., 2017). As one of the most popular anaerobic processes, upflow anaerobic sludge blanket (UASB) was successfully applied and established wide acceptance in domestic wastewater treatment, especially in tropical and subtropical regions (Lohani et al., 2016). An important advantage of UASB was the formation of granular sludge with excellent settling characteristics, high biomass concentration and abundant microorganisms, which contributed to vigorous wastewater-granule contact and rapid degradation of organic matter in wastewater (Abbasi and Abbasi, 2012; Reino and Carrera, 2017). To achieve a successful and stable operation of UASB reactor, the start-up period was a critical step, and its primary task was to cultivate granular sludge with high activity and high mechanical strength as soon as possible (Subramanyam and Mishra, 2013). While sludge granulation was a complex process, it was easily affected by numerous physical, chemical or even biological factors (Abbasi and Abbasi, 2012; Liu et al., 2003; Luo et al., 2016). The long start-up period was a major obstacle to UASB reactor, which usually took two months or even longer at low concentrations of substrate, low load and low temperature conditions (Gupta et al., 2016). This reduced the attractiveness of UASB and hindered its application.

In anaerobic bioreactors, wastewater-biomass mass transfer played an important role in organic matter removal and methane production (Luo et al., 2016). Whereas, natural turbulence produced by low upflow velocity (V_{up}) and low biogas production was difficult to maintain sufficient wastewater-biomass contact during the start-up of UASB reactor treating domestic wastewater. Sludge was easily deposited at the bottom of UASB reactor and mass transfer limitations occurred due to lack of adequate mixing, which had a negative impact on granulation (Reino and Carrera, 2017). Many studies have been conducted to accelerate granulation and shorten the start-up time of UASB reactor. For instance, enhanced granulation was achieved by adding specific materials, such as polymer, inert matter and multivalent cations (Abbasi and Abbasi, 2012; Lu et al., 2015a; Xu et al., 2015). However, this method was still weak in improving wastewater-biomass mass transfer and shortening start-up time. The expanded granular sludge bed (EGSB) reactor and the internal circulation reactor significantly improved sludge distribution and mass transfer due to upflow hydraulic circulation (Luo et al., 2016), but a high V_{up} was likely to cause the seeded flocculent sludge to be washed out during start-up period and hence hindered granulation.

The released biogas in anaerobic treatment of domestic wastewater could be utilized as an energy product. However, a significant amount of methane could not be recovered because a large proportion was dissolved in the effluent, regardless of biogas exhibiting higher methane contents (70–78%) (Souza et al., 2011). Liquid-to-gas mass transfer was crucial in anaerobic processes, which was investigated theoretically and experimentally among different methanogenic reactors, and the results demonstrated that mass transfer limitations and supersaturation of dissolved methane were ubiquitous (Pauss et al., 1990). Anaerobic wastewater treatment processes such as UASB, which usually depended on settling for sludge retention, mass transfer of CH_4 from liquid to headspace was limited because of low liquid V_{up} and poor mixing (Souza et al., 2011; Yeo and Lee, 2013). For such processes treating domestic wastewater or similar low-strength wastewater, the degree of supersaturation and losses of dissolved methane reached 1.3–6.9 and 11–100% of total methane production, respectively (Bandara et al., 2012; Bandara et al., 2011; Cookney et al., 2016; Singh et al., 1996).

Improved mass transfer by upflow hydraulic and biogas circulation in anaerobic system has been demonstrated previously (Yeo and Lee, 2013), but the use of downflow sludge circulation to enhance mass transfer, granulation and methane recovery has rarely been reported. An anaerobic reactor used in this study subverted the process principle of conventional anaerobic upflow mass transfer and put forward the concept of sludge downflow mass transfer. The sludge at the bottom of reactor was first raised to a certain height and then released downward, forming a reverse wastewater-sludge flow and intense mass transfer. In this way, the sludge could remain suspended and evenly distributed in the reaction zone. Improved mixing and liquid-to-gas mass transfer by sludge circulation enhanced the stripping of CH_4 from the liquid phase, which resulted in dissolved CH_4 concentration near to thermodynamic equilibrium and finally enhanced methane recovery.

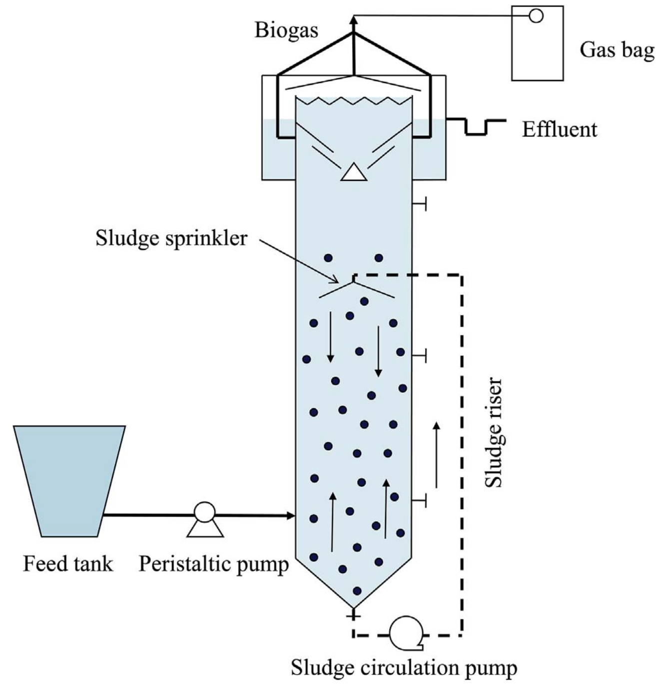

Fig. 1. The schematic diagram of the modified UASB reactor.

The aim of this study was to (i) explore a suitable method for achieving rapid start-up of anaerobic reactor at low load in domestic wastewater treatment; (ii) evaluate the effects of enhanced mass transfer by downflow sludge circulation on granulation and methane recovery; (iii) reveal the dynamic evolution and composition of microbial community during start-up in the existence of downflow sludge circulation.

2. Materials and methods

2.1. Experimental configuration and operation

The reactor comprised a Perspex column of 120 cm in total height and 20 L in total effective volume (Fig. 1). It was mainly composed of three parts, the bottom part was a cone (height of 10 cm), the middle part of the column was a cylinder (diameter of 14 cm, height of 90 cm) and a gas-liquid-solid separator (diameter of 19 cm, height of 20 cm) was designed as the upper part. The introduction of downflow sludge circulation system was an important improvement of the reactor, and it included a micro sludge circulation pump (DC40F-2460, Shenzhen Zhongke Century Technology Co., Ltd., China), a sludge riser and a sludge sprayer. Among them, the micro sludge circulation pump controlled the rate of sludge circulation through a regulator to provide suitable shear force for the growth of sludge at different stages. The influent was controlled by a peristaltic pump (BT100-2J, Longer Pump Co., Ltd., China) for maintaining different HRT, and the effluent from reactor outlet flowed into a sealed U-tube to prevent the escape of biogas and access of outside air.

The reactor was operated for 120 days continuously, which were divided into three different stages (stage I-III) based on decreased HRT (Table 1). HRT was reduced in steps when the reactor reached a relatively stable state in terms of SCOD removal efficiency, biomass concentration and biogas production under the designed organic loading rate (OLR). To avoid excessive sludge loss, guarantee sufficient