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Granular activated carbon as nucleating agent for aerobic sludge granulation: Effect of GAC size on velocity field differences (GAC versus flocs) and aggregation behavior

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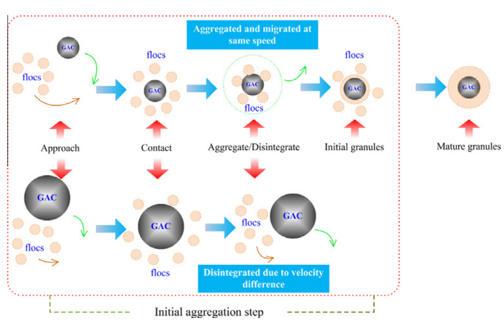
HIGHLIGHTS

- Addition of GAC performed as the nucleating agent which facilitated granulation.
- A novel quantitative evaluation method was used to investigate granulation process.
- Increase the size of GAC enlarged velocity field differences between flocs and GAC.
- Increase velocity field differences inhibited flocs–GAC coaggregates.
- GAC with suitable size can perform as the nucleating agent to favor granulation.

GRAPHICAL ABSTRACT



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ABSTRACT

Initial cell aggregation plays an important role in the formation of aerobic granules. In this study, three parallel aerobic granular sludge reactors treating low-strength wastewater were established using granular activated carbon (GAC) of different sizes as the nucleating agent. A novel visual quantitative evaluation method was used to discern how GAC size affects velocity field differences (GAC versus flocs) and aggregation behavior during sludge granulation. Results showed that sludge granulation was significantly enhanced by addition of 0.2 mm GAC. However, there was no obvious improvement in granulation in reactor amended with 0.6 mm GAC. Hydraulic analysis revealed that increase of GAC size enhanced the velocity field difference between flocs and GAC, which decreased the lifecycle and fraction of flocs–GAC aggregates. Overall, based on analysis of aggregation behavior, GAC of suitable sizes (0.2 mm) can serve as the nucleating agent to accelerate flocs–GAC coaggregation and formation of aerobic granules.

1. Introduction

Aerobic sludge granulation is known as an emerging technology for domestic and industrial wastewater treatment in recent years (Lee et al., 2010; van Loosdrecht and Brdjanovic, 2014). Compared

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with conventional activated sludge, granular sludge has multiple advantages such as dense structure, excellent settling ability, and high pollutant removal efficiency (de Kreuk et al., 2005; Lee et al., 2010). These characteristics enable granular sludge to decrease the footprint by up to 75% and save up to 25% in energy costs (Beun et al., 2002).

Previously, most aerobic granular sludge processes have been used to treat high or medium-strength wastewaters with organic loading rates (OLR) of 2.5–15 kg COD m^{-3} d^{-1}. Previous researches have shown that high influent OLR facilitates the formation of aerobic granules (de Kreuk and van Loosdrecht, 2006; de Kreuk et al., 2010; Sheng et al., 2010). For treatment of domestic wastewater (influent COD concentration generally below 500 mg L^{-1}), sludge granulation requires a relatively long start-up period (more than 3 months), with aerobic granules unstable under low OLR (Liu and Liu, 2006; Li et al., 2008; Yilmaz et al., 2008; Sheng et al., 2010). Therefore, application of aerobic granular sludge for treating low-strength domestic wastewater represents an important challenge (Ni et al., 2009; Liu et al., 2010; Lotito et al., 2012).

Granulation of aerobic sludge occurs when microorganisms contact and attach to form initial nuclei. The nuclei subsequently aggregate with the cell-to-cell self-immobilization and conglutinated by extracellular polymeric substances (EPS). Eventually, mature granular sludge forms with large size (larger than 0.5 mm) and spherical shape (Liu and Tay, 2002; Barr et al., 2010; Pijuan et al., 2011; Wan et al., 2014). The initial aggregation step plays an important role during sludge granulation (Liu and Tay, 2002; Lv et al., 2014). Favorable hydrophobicity and electrostatics enhance initial aggregation and accelerates microbial granulation (Liu and Tay, 2002; Wan et al., 2011; Bubakova et al., 2013; Lv et al., 2014). However, low organic concentration in influent is reported to decrease cell hydrophobicity, EPS secretion and microbial growth (Tay et al., 2004). Consequently, microbes are loosely attached and the initial nuclei are easily disintegrated by collision forces including the hydraulic shear stress, making granulation hard to achieve (Wang et al., 2009).

To enhance granulation of aerobic sludge treating low-strength domestic wastewater, inert particles or debris detached from granular sludge have been shown to serve as initial nuclei (Tay et al., 2004; Wang et al., 2009). These nucleating agents have favorable surface properties that enhance initial aggregation and resist collision forces including the hydraulic shear stress (Wan et al., 2011; Zhou et al., 2013). Previous studies showed that hydraulic conditions, such as the flow regime during the initial aggregation step can also influence aggregation behavior (Wan et al., 2011). Homogenous circular flow was reported to facilitate aggregation and accelerate microbial granulation (Liu and Tay, 2002; Wan et al., 2011). Previous studies have focused on how such nucleating agents influence the granular structure and associated microbial community (Zima et al., 2008; Wan et al., 2011). However, their effects on hydraulic conditions that influence the granulation process (e.g., velocity field differences between flocs and the nucleating particles) are poorly understood.

In this study, different sizes of granular activated carbon (GAC) were used as the nucleating agent in three parallel bioreactors treating low-strength domestic wastewater. The granulation process was investigated using high-speed Charge-Coupled Device (CCD) visualization technology. The objectives were to (i) quantify how GAC size affects velocity field differences between flocs and GAC, (ii) characterize the effects of velocity field differences between flocs and GAC on sludge aggregation behavior and eventual granulation, and (iii) advance mechanistic understanding of how hydraulic regimes influence the sludge granulation process.

2. Methods

2.1. Reactor setup and operation

Three parallel Plexiglas sequencing batch reactors (SBR) with effective volumes of 10 L were used in this study. The reactors had an internal diameter of 12.0 cm and a ratio of height to diameter (H/D) of 10:1. The SBR cycle length was 4 h with 10 min of feeding, 210 min of aeration, 10 min of settling and 10 min of withdrawal. The effluent was set at the height of 5 L volume in all the reactors, and the volumetric exchange ratio was 50%. Air was introduced by a fine-bubble porous aerator placed at the bottom of the reactors, and the superficial up-flow air velocity was 1.0 cm s^{-1}. High-quality coconut-shell GAC was used, with a specific surface area of 495–567 m^2 g^{-1} and apparent density of 1.11–1.27 g cm^{-3}. In a preliminary experiment, various sizes of GAC were inoculated in reactors and run for 48 h. Results showed that the GAC should be at least 0.16 mm to be retained in the reactors. As a control group, *R*1 was run without GAC, and 0.2 mm and 0.6 mm GAC was added in *R*2 and *R*3, respectively. The dosage of GAC was 1000 mg L^{-1} for these reactors.

The influent COD concentration of the three reactors was 503 ± 25 mg L^{-1}, and the OLR was about 1.5 kg COD m^{-3} d^{-1}. The composition of synthetic wastewater was as follows (mg L^{-1}): sodium acetate, 628; sucrose, 46.3; NH_4Cl, 120.18; KH_2PO_4, 27.17; K_2HPO_4, 34.72; yeast, 125; peptone, 187.5; $CaCl_2$, 80; and $MgSO_4$, 30. Additionally, a trace element solution comprised of the following components was added (mg L^{-1} in final wastewater): H_3BO_3, 0.05; $CuSO_4{\cdot}5H_2O$, 0.05; $ZuSO_4{\cdot}7H_2O$, 0.05; $AlCl_3$, 0.09; $CoCl_2$, 0.05; $MnSO_4{\cdot}H_2O$, 0.05; $(NH_4)_2Mo_7O_{24}$, 0.05; $NiCl_2{\cdot}6H_2O$, 0.09; and $FeSO_4{\cdot}7H_2O$, 0.05. Room temperature was maintained at 25 ± 2 °C.

The seed sludge was collected from an aerobic tank at Qige municipal wastewater treatment plant in Hangzhou, China. The sludge volume index (SVI_{30}) of seed sludge was approximately 125 ± 17 mL g^{-1}. The seed sludge had loose morphology with mean diameter of 62 ± 2.4 μm.

2.2. Analysis of hydraulic and aggregating characteristics

An identical plexiglas cylinder tube was built to investigate the velocity field of the nucleating agent (GAC) or flocs, and the aggregation behavior of flocs–GAC aggregates. To avoid the effect of light refraction in the cylindrical tube, the device was immersed in a rectangular plexiglas tank filled with water. Air was introduced from the bottom of reactor, and the superficial up-flow air velocity was 1.0 cm s^{-1}. At the same time, a Light Emitting Diode (LED) lamp was situated in front of plexiglas tank as supplementary lighting. A high-speed CCD camera (Vieworks, VH-2MG2-M42A0, Korea) with 42 frames per second (42 fps) was installed on a lifting platform horizontally controlled by stepper motor in front of plexiglas tank. 1600 × 1200 pixel images were taken by a TV lens (PENTAX, Japan), and then transferred through a GigE network and recorded on a computer.

The background was divided into a dynamic threshold module by image processing. Different locations of GAC or flocs in interval images (Δr) and time intervals (Δt) permitted velocity calculations (v) (Díez et al., 2007; Zima et al., 2008). The velocity was calculated as follows:

$$v = \frac{\Delta r}{\Delta t} \quad (1)$$

where v is the velocity of GAC or flocs (cm s^{-1}), Δr is the position difference of GAC or flocs in interval images (cm), and Δt is the time interval (s).