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Review

Aerobic granular processes: Current research trends

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HIGHLIGHTS

- Recent R&D works for aerobic granular process were reviewed.
- Treatments, granulation mechanisms and stability, and waste reuse were covered.
- Challenge and prospect for commercialization of aerobic granular process were discussed.

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ABSTRACT

Aerobic granules are large biological aggregates with compact interiors that can be used in efficient wastewater treatment. This mini-review presents new researches on the development of aerobic granular processes, extended treatments for complicated pollutants, granulation mechanisms and enhancements of granule stability in long-term operation or storage, and the reuse of waste biomass as renewable resources. A discussion on the challenges of, and prospects for, the commercialization of aerobic granular process is provided.

Contents

1. Introduction

Aerobic granules are aggregates with functional strains that are embedded in a matrix of extracellular polymeric substances (EPS), inorganic compounds and various minerals (Adav and Lee, 2008). Large aggregates with a compact structure settle rapidly in water (Wu and Lee, 1998). Aggregates with compact interiors have high diffusional resistances toward foreign molecules and, therefore, high tolerance of the toxicity of feed to their constituent cells (Adav et al., 2007a,b). Most aerobic granules are large and have a compact interior, and so are proposed for use in the biological treatment of high-strength industrial wastewaters (Adav et al., 2008; Lee et al., 2010; Show et al., 2012; Khan et al., 2013).

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Studies of all aspects of processes that involve aerobic granules have been published. A Web of Science™ database search for the term "aerobic granules" or "aerobic granular sludge" on 2015. Nov.11 yielded a total of 840 papers in fields such as Biotechnology and Applied Microbiology (364), Environmental Sciences (324), and Environmental Engineering (238). Authors from China and Singapore were responsible for around 63% of these papers. Of all platforms, Bioresource Technology has published the most papers on aerobic granules (111), followed by Applied Microbiology and Biotechnology (73) and Water Research (68). The total number of citations of these papers is approximately 15,500, with 2124 and 2230 hits in 2013 and 2014, respectively, suggesting that this research topic is a current focus. Relevant articles with more than 300 citations can be found (Beun et al., 1999; Liu and Tay, 2002, 2004).

This mini-review presents recent studies of current R&D efforts in formation, operation and storage stability of aerobic granules, and the potential use of waste biomass as a resource for beneficial application. Challenges of, and prospects for, this biological process are presented.

2. Extensive wastewater treatment

Aerobic granules were tested for their effectiveness in treating industrial effluent with high chemical oxygen demand (COD). Recent investigations have addressed the treatment of complicated effluents. For example, Romos et al. (2015) used aerobic granules to treat wastewater that contains phenol, *o*-cresol and *p*-nitrophenol sith up to 29 g mixed salts/L. The cultivated granules achieved the complete biodegradation of the aromatic compounds under high salinity conditions. Long et al. (2014a) utilized mature aerobic granules to treat municipal sludge and deep dewatering filtrate, and noted that their aerobic granules maintained structural stability for 84 d of operation. Zhao et al. (2015) utilized aerobic granules to treat organic pollution by pharmaceuticals and personal care products (PPCPs). The cultivated granules promoted the growth of Proteobacteria, Bacteroidetes, Betaproteobacteria and Zoogloea to remove some, but not all, of the PPCPs tested.

Studies of the feasibility of using aerobic granules for removing biological nutrients (with N and P) or other pollutants have recently been published. Yu et al. (2014a) used aerobic granules to treat high-strength ammonium wastewater and found that granular adsorption was responsible for 9% of the total nitrogen removal and nitrification–denitrification in granules was responsible for 76%. The dissolved oxygen level is useful for regulating the performance of wastewater treatment. Wei et al. (2014) formed aerobic granules for the simultaneous removal of nitrogen and phosphorus from high-strength ammonia wastewater in a sequencing batch reactor (SBR). They utilized the alternative influence COD/N ratio to improve the removal of nitrogen and phosphorus.

To save both energy and the substrate, research into aerobic granular processes has focused on partial nitrification for denitrification (Rathnayake et al., 2015). Liang et al. (2015) seeded partial nitrification granules to cultivate aerobic granules that suppressed the growth of nitrite-oxidizing bacteria. In so doing, they successfully cultivated partial nitrification granules that contained *Nitrosomonas* as the predominant ammonia-oxidizing bacteria. Wan et al. (2014a) used a partial nitrification aerobic granular reactor using ammonia laden wastewaters. They successfully achieved the balanced growth of ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) in cultivated granules. Wan et al. (2014b) used aerobic granules to perform the partial nitrification of highly saline wastewaters in a continuous-flow reactor. The cultivated granules exhibited a >95% nitrite accumulation rate and a >85% COD removal rate at a salinity of 50 g/L. Jemaat et al. (2014) utilized an aerobic granular process to achieve simultaneous partial nitritation and o-cresol biodegradation in a continuous-flow reactor. Neither p-nitrophenol nor phenol inhibited partial nitritation and o-cresol biodegradation reactions but 2-chlorophenol did so.

Ab Halim et al. (2015) cultivated aerobic granules at 50 °C at an influent organic loading rate (OLR) of 1.6 COD kg/m^3 d and a COD/N ratio of 8. The cultivated granules had an average diameter of 3.36 mm and removed high levels of COD, ammonia and phosphate. The study revealed that aerobic granules that are cultivated at 50 °C can be used in a warm climate.

Conventional aerobic granular processes were focused on the removal of COD. Current literature focuses on the simultaneous removal of multi-pollutants, particularly COD and nitrogen, by aerobic granules and on the removal processes under high salinity or thermophilic conditions. Also, the co-removal of specific pollutants such as PPCPs using aerobic granular processes is an interesting development for future studies.

3. Granulation mechanism

Aerobic granulation can be performed only with relatively small ranges of operational parameters, including type of inoculum, feed composition and OLR, feeding strategy, reactor geometry, aeration intensity, setting time, and volumetric exchange ratio (Adav et al., 2008). However, a comprehensive granulation mechanism is yet to be established. Progress has been made in understanding how granulation occurs and how the process can be accelerated.

Chen and Lee (2015) examined the role of seed sludge in aerobic granulation processes and noted that sludge samples that are collected in warm seasons can be utilized to cultivate aerobic granules. When sludge samples that were collected in cold weather were used, no granulation occurred. These authors claimed that since *Brevundimonas* sp., which is an effective EPS producer, can grow at about 30 °C, and was present in their warm weather samples, aerobic granules can be formed with the formed excess EPS. Without this functional strain, aerobic granulation could not occur. Cydzik-Kwiatkowska (2015) correlated the microbial composition of biomass with the kinetics of nitrogen conversions in aerobic granular reactors to treat high-ammonium wastewaters. Their studied granules contained Proteobacteria and Actinobacteria as predominating strains in the bacterial community, and the granules became enriched with bacteria that produced extracellular polymeric substances (EPS). The evolution of autotrophic and heterotrophic nitrifiers is noted to depend on the aeration intensity and nitrogen loading in the wastewater.

Liu et al. (2015) studied the performance of aerobic granular sludge processes in the treatment of slaughterhouse wastewater. The formed granules provided higher removal ratios of COD, ammonia and phosphate than the seed-activated sludge. The authors noted a relationship between granule size and microbial community: granules of size 0.6–1.2 mm were preferred by AOB and those of size 1.2–1.8 mm were preferred by NOB. Dahalan et al. (2015) obtained size profiles under non-phototrophic and phototrophic conditions. They proposed that activated sludge flocs were firstly converted to aerobic granules by increasing the biomass concentration in bioreactors, which process also increased the granule size. Tijani et al. (2015) characterized aerobic granules using fractal geometry and claimed that their internal structure was close to that of a compact sphere that is formed by cluster–cluster aggregation mechanisms. Aggregate structure affects suspension filterability (Chen et al., 1996). The porosity of the granules was reported to be 0.68, which is much lower than those of activated sludge flocs (>0.9).