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Rheological and fractal hydrodynamics of aerobic granules

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HIGHLIGHTS

- Microbial bioactivity are maintained during granulation.
- Granules constitutes significant structural framework.
- Scaling relationships based on fractal geometry are vital in granulation.

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ABSTRACT

The structural and hydrodynamic features for granules were characterized using settling experiments, predefined mathematical simulations and *ImageJ*-particle analyses. This study describes the rheological characterization of these biologically immobilized aggregates under non-Newtonian flows. The second order dimensional analysis defined as $D_2 = 1.795$ for native clusters and $D_2 = 1.099$ for dewatered clusters and a characteristic three-dimensional fractal dimension of 2.46 depicts that these relatively porous and differentially permeable fractals had a structural configuration in close proximity with that described for a compact sphere formed via cluster–cluster aggregation. The three-dimensional fractal dimension calculated via settling-fractal correlation, $U \propto l^D$ to characterize immobilized granules validates the quantitative measurements used for describing its structural integrity and aggregate complexity. These results suggest that scaling relationships based on fractal geometry are vital for quantifying the effects of different laminar conditions on the aggregates' morphology and characteristics such as density, porosity, and projected surface area.

1. Introduction

Different safe biological systems have been employed in recent years at minimizing the impact of toxic waste on the ecosystem. Aerobic granulation is a unique microbial immobilization technology developed in recent years based on the activated sludge system to produce aerobic granules for wastewater treatments. These granules constitute a specialized microbial biofilm composed of densely packed aggregates of self-immobilized cells which may degrade organic and inorganic components of the waste. Previous researches indicated that biofilm is one of the most efficient techniques for wastewater treatment as compared to its conventional suspended activated sludge systems. This is due to its compact structure developed under the sequencing batch reactor (SBR) operations (Tay et al., 2004; Yang et al., 2007; Abdullah et al., 2011).

Aerobic granulation system fed with palm oil mill effluent (POME) as substrate previously developed by Abdullah et al. (2011) in an SBR was proven efficient for treating high strength effluent discharges. Excellent reactor performances was observed in settling ability, mass transfer efficiency, differential sludge-effluent phase separation, biomass retention, resilience to shock loadings and bioactivity in stable granules formation using POME. Thus, the use of activated sludge reactors for treatment applications of industrial and pharmaceutical wastes under cyclic aerobic systems serves as succeeding alternative for effluent treatments.

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The adhesive principle of microorganisms to defined surfaces, suspended particles and other microorganisms is pervasive in nature and is required for the proper operation of bioreactors. Within these suspended-growth bioreactors, microbial self-induced flocculation occurs through cell-to-cell attachment, resulting in the formation of rapid-settling granules which enables efficient removal of biomass from the fluid suspension. The irregularity in shape and compressibility features common to these biological aggregates, makes it reprehensible to compute granule geometrical characteristics such as density, porosity and fluid collection properties. These granules' characteristics are contributive to efficient design of granulation system aimed for single-column operation. For an accurate computations, fractal dimensional geometry has been established to define these highly frail structures so as to promote the understanding of the influence of a wide array of granulation phenomena such as turbulence, shear abrasion and fluid kinetics.

The fractal geometry of granular aggregates can be determined via scaling relationship. For Euclidean aggregates, the three dimensional fractal dimension (D_3) is 3; however, granular aggregates exhibit significantly lower fractal dimensions. Simulation models developed to describe the random processes of aggregate formation is related to the magnitude of their fractal dimensions. Granules cultivated through particle-to-cluster and cluster-to-cluster aggregation have three-dimensional fractal dimensions in the range of 2.5–3.0 (Logan and Wilkinson, 1991; Maggi, 2007). The weak structure of immobilized aggregates can be attributed to the random mobility of its adhesive particles due to their inability to penetrate the aggregates resulting in particle collision and adherence on the aggregate exterior. This mode of aggregation is termed as substrate-limited granular immobilization (SLGI) and results in formation of well-defined aggregates with D_3 values greater than 2.

For granular aggregates cultivated under laminar flow systems, the presence of two distinct regimes of flocculation indicates that fractal scaling calculations can be used to describe the formation mechanism and structural compactness. Lin et al. (2003) proposed that fractal dimensions are proximally identical for aggregates developed under similar reactor conditions. However, the simulation models defined for fractal calculations have varied with different forms of microbial aggregates. This indicates that such generalization are yet to be established because bioflocs aggregation via particle collisions experienced varying flocculation mechanisms, such as sub-mechanical and turbulent shear as well as different sedimentation.

According to Mohammed et al. (2013), the microbial networks that constitute the granules formation are formed by intra- and inter-linked bridges of the cellular surface appendages. Although the adhesive strength of these immobilized microbial consortium is not uniform throughout the granules' layers, specific internal and external forces tends to promote their coagulation into well-defined structures. Thus, the prospect for other flocculation mechanisms, the unpredictability in the microbes' consortium and population generate variations in the aerobic granulation systems is characterized by fractal analyses.

This research aims to determine if a universal fractal equation can be developed for in-stored granules cultivated from palm oil mill effluent (POME). Recent studies have proven that these microbial aggregates are efficient in for successful treatment of agro-based wastewater such as POME (Abdullah et al., 2013, 2011). In this study, additional characterization of the rheological hydrodynamics of granules will be provided. The fractal relationships are also compared to its Euclidean replicas under similar hydraulic systems. We calculate the granules' three dimensional geometries and discuss the transcendence of fractal calculations via settling-fractal simulations.

2. Methods

2.1. Bio-flocculation characteristics of activated sludge

Bio-flocculation was established by exerting a low centrifugal force which slowly mixes the sludge sample at 15 rpm for 10 min. The fluid viscosity of the sub-mechanical granulation system was also evaluated to reflect the settling ability, compressibility and structural compactness of the microbial association within granules.

The concentrated mass (m_o) of the fractal aggregates was determined by using electronic microbalance (AEM-5200, Shimadzu, Japan). The spatial volume (υ_o) was determined from its diameter sizes (d_o) and their projected surface area as visualized by the image analysis system. The density of the aerobic granules (ρ_o) were calculated via the mathematical expression as given in Eq. (1):

$$\rho_o = \frac{m_o}{\upsilon_o} \tag{1}$$

The mass of an emptied graduated measuring cylinder (m_c), volume of the mixed-liquor (υ_l) and the coupled mass after filling the measuring cylinder (m_{c+l}) were measured to determine the density of the mixed-liquor (ρ_l) in the SBRs following Eq. (2):

$$\rho_l = \left[\frac{m_{c+l} - m_c}{\upsilon_l}\right] \tag{2}$$

According to the well-known Stokes equation, the viscosity (μ) of the fluid media in a laminar flow system of the SBR was calculated as described by Li and Yuan (2002) in Eq. (3):

$$\mu = \left[\frac{g(1-\varepsilon)(\rho_c - \rho_l)d_o^2}{18U_{act}}\right] \tag{3}$$

ε, U_{act} and d_o are the degree of porousness, actual settling velocity and diameter of a specific granular aggregate, respectively.

2.2. Hydrodynamic features

For a porous bacterial aggregate, it is assumed that there are N identical cells. Each cell has a dry solid mass (m_d) when dewatered and a wet mass (m_o) and density (ρ_o) when the immobilized aggregates remained native. Theoretically, the porosity of an individualized granule of mass, m_o with an impermeable Euclidean volume, V_a and an enclosed spatial volume, υ_o are defined by the cumulative number of granular aggregates, N constituting the granulation system as described in Eq. (4):

$$\text{Porosity } (\varepsilon) = \left[1 - \frac{N\upsilon_o}{V_a}\right] \tag{4}$$

Deducing a volume-based equation from Xiao et al. (2008) $\frac{N\upsilon_o}{V_a} = \frac{6fm_d}{\pi\rho_o d^3}$ thus, Eq. (4) becomes

$$\varepsilon = \left[1 - \frac{6fm_d}{\pi\rho_o d^3}\right] \tag{5}$$

f is a dimensionless ratio between the wet mass and dry mass of each granular aggregate; $f = m_c/m_d$. The overall density difference between the bacterial aggregates and water is a function of the porosity and calculated as by Eq. (6):

$$\rho_c = \left[\rho_l + \frac{(\rho_o - \rho_l)}{1-\varepsilon}\right] \tag{6}$$

ρ_c is the density of the bacterial cells; ρ_o and ρ_l are the densities of the granules and the mixed-liquor, respectively (Li and Yuan, 2002). The granules were observed as porous and highly fractal, a