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Biomass density and filament length synergistically affect activated sludge settling: Systematic quantification and modeling

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ABSTRACT

Settling of the biomass produced during biological treatment of wastewater is a critical and often problematic process. Filamentous bacteria content is the best-known factor affecting biomass settleability in activated sludge wastewater treatment systems, and varying biomass density has recently been shown to play an important role as well. The objective of this study was to systematically determine how filament content and biomass density combine to affect microbial biomass settling, with a focus on density variations over the range found in full-scale systems. A laboratory-scale bioreactor system was operated to produce biomass with a range of filamentous bacterium contents. Biomass density was systematically varied in samples from this system by addition of synthetic microspheres to allow separation of filament content and density effects on settleability. Fluorescent in-situ hybridization indicated that the culture was dominated by *Sphaerotilus natans*, a common contributor to poor settling in full-scale systems. A simple, image-based metric of filament content (filament length per floc area) was linearly correlated with the more commonly used filament length per dry biomass measurement. A non-linear, semi-empirical model of settleability as a function of filament content and density was developed and evaluated, providing a better understanding of how these two parameters combine to affect settleability. Filament content (length per dry biomass weight) was nearly linearly related to sludge volume index (SVI) values, with a slightly decreasing differential, and biomass density exhibited an asymptotic relationship with SVI. The filament content associated with bulking was shown to be a function of biomass density. The marginal effect of filament content on settleability increased with decreasing biomass density (low density biomass was more sensitive to changes in filament content than was high density biomass), indicating a synergistic relationship between these factors. Consideration of both biomass density and filament content, as by the methods and model described herein, should improve operation and troubleshooting of settling processes for biological solids.

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1. Introduction

A critical and frequently problematic unit process of domestic and industrial biological wastewater treatment systems is the removal by sedimentation of the microbial biomass produced during growth on wastewater contaminants. Activated sludge, the most common biological wastewater treatment technology in industrialized countries, is comprised of one or more biological reactors in series, where wastewater contaminants are consumed and transformed by suspended microorganisms, followed by sedimentation tanks (secondary clarifiers), where this biomass is separated from the treated effluent stream. A portion of the settled biomass is wasted from the system, and a portion is recycled back to the biological reactors. Poorly settling biomass can severely limit clarifier capacity (and thereby overall plant capacity), result in poor quality effluent, reduce the capacity of downstream solids handling processes, and, in severe cases, can lead to washout (loss of large quantities of biomass in the clarifier effluent).

The microorganisms (primarily bacteria) in activated sludge systems grow and agglomerate as flocs, and the characteristics of these flocs largely control biomass settling rates. A large body of research has been devoted to studying factors that affect settling, with filamentous bacteria content the best-known of these (reviewed in Jenkins et al., 2003; Martins et al., 2004). Floc surface properties, shape, size, extracellular polymeric substances, and flocculating ability are also known to affect biomass settleability (Andreadakis, 1993; Banadda et al., 2005; Grijspeerdt and Verstraete, 1997; Jin et al., 2003; Li and Yang, 2007; Liao et al., 2006; Magara et al., 1976; Urbain et al., 1993; Wilen et al., 2003).

Biomass density (defined as biosolids mass/biosolids volume, not including pore spaces) has recently been demonstrated to be an important factor affecting activated sludge settling in both laboratory and full-scale systems (Jones and Schuler, 2010, 2012; Kim et al., 2010; Schuler and Jang, 2007a, b; Schuler et al., 2001), and it appears to contribute to seasonal variability in settling (Jones and Schuler, 2010) and process upsets affecting settling (Jones and Schuler, 2012). The laws of physics dictate that biomass density affects settling rates, since the gravitational force that drives sedimentation is a linear function of the difference between the biomass and liquid densities (the buoyant density). The practical importance of biomass density effects on settleability, however, depends on the degree to which this density varies in activated sludge systems. Nearly all previous studies of filament effects on settleability have implicitly assumed constant biomass density across samples. However, it has been demonstrated that activated sludge biomass density varies widely in full-scale systems; for example, it was found to vary from 1.022 to 1.056 g/mL in analyses of 17 full-scale systems, which corresponds to a 255% variation in gravitational force for a liquid density of 1 g/mL (Schuler and Jang, 2007a). Biomass density has been demonstrated to vary due to differing polyphosphate content, non-volatile suspended solids, solids retention time, and inclusion of a biofilm phase (Kim et al., 2010; Schuler and Jang, 2007a; Schuler et al., 2001).

There have been many previous attempts to quantify the effects of filament content on settleability in activated sludge systems, with varying results (reviewed in Schuler and Jassby, 2007). However, to date there has been no systematic effort to determine filament and density effects by controlled variation of these variables, or with filament quantification by filament length, rather than the less sensitive Filament Index scale based on examination of microscopic images (Schuler and Jang, 2007a). It was hypothesized that variable biomass density and filament content affect settleability in a predictable way, and that variations in biomass density may help to explain some of the previously reported variability in filament content effects.

The objective of this study was to systematically determine the combined effects of filamentous growth and density effects on activated sludge settleability, using samples from a laboratory reactor covering a broad range of filament content values, combined with a recently-developed method for varying biomass density through the addition of synthetic microspheres (Schuler and Jang, 2007c). A better fundamental understanding of how the factors of density and filament content combine to affect settling should help in the interpretation of previous studies focusing on filamentous growth alone, it should aid in troubleshooting settling problems in existing systems, and it should improve the basis for rational operation and design for improved solids separation.

2. Methods

2.1. *Reactor configuration and operation*

A 16 L, continuous flow reactor was operated to produce an activated sludge biomass with a range of filament contents. An Eckenfelder-type reactor was used, with a baffled, in-reactor settling zone eliminating the need for a separate clarifier and solids recycle line. The reactor was aerated and mixed continuously, and pH was between 7 and 7.5. Temperature was ambient at 23 ± 1 °C. Synthetic wastewater with glucose and yeast extract as primary carbon sources, demonstrated to enrich for filamentous bacteria in a previous bulking study (Liao et al., 2004), was continuously added with a hydraulic residence time of 12 h. The solids retention time (SRT) was controlled at four days by daily wasting directly from the reactor. The reactor was inoculated with activated sludge obtained from the South Durham Water Reclamation Facility, located in Durham, North Carolina. The South Durham plant is a five-stage Bardenpho-type plant (anaerobic, anoxic, aerobic, anoxic, aerobic reactor sequence, with an internal high nitrate recycle from the final aerobic to the first anoxic reactor for improved denitrification), a configuration designed to perform enhanced biological phosphorus removal (EBPR). Two experimental runs were performed in sequence, with the first inoculation on day 0, and the second on day 18, after the reactor was emptied and washed.

2.2. *Analytical methods*

Total suspended solids (TSS) and volatile suspended solids (VSS) were measured using standard methods 2540B and