Effects of integrated fixed film activated sludge media on activated sludge settling in biological nutrient removal systems

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A B S T R A C T

Integrated fixed film activated sludge (IFAS) is an increasingly popular modification of conventional activated sludge, consisting of the addition of solid media to bioreactors to create hybrid attached/suspended growth systems. While the benefits of this technology for improvement of nitrification and other functions are well-demonstrated, little is known about its effects on biomass settleability. These effects were evaluated in parallel, independent wastewater treatment trains, with and without IFAS media, both at the pilot (at two solids residence times) and full scales. While all samples demonstrated good settleability, the Control (non-IFAS) systems consistently demonstrated small but significant (p < 0.05) improvements in settleability relative to the IFAS trains. Differences in biomass densities were identified as likely contributing factors, with Control suspended phase density > IFAS suspended phase density > IFAS attached phase (biofilm) density. Polyphosphate content (as non-soluble phosphorus) was well-correlated with density. This suggested that the attached phases had relatively low densities because of their lack of anaerobic/aerobic cycling and consequent low content of polyphosphate-accumulating organisms, and that differences in enhanced biological phosphorus removal performance between the IFAS and non-IFAS systems were likely related to the observed differences in density and settleability for the suspended phases. Decreases in solids retention times from 8 to 4 days resulted in improved settleability and increased density in all suspended phases, which was related to increased phosphorus content in the biomass, while no significant changes in density and phosphorus content were observed in attached phases.

1. Introduction

Stable and efficient removal of the biological solids produced in biological reactors is critical to the operation of biological wastewater treatment systems for the production of high quality effluent. Activated sludge is the most common biological wastewater treatment technology used in industrialized countries, and in this process biological solids are...
removed by sedimentation. Poor settling of biological solids remains one of the most common operational problems in activated sludge wastewater treatment systems around the world (Martin et al., 2004). This can lead to increased solids treatment costs, increased effluent solids concentrations, decreased disinfection efficiencies, and increased risks to downstream ecosystems and public health.

Considerable research effort has focused on the effects of morphological characteristics, such as floc size (Knocke, 1986) and shape (Banada et al., 2005; Eriksson and Hardin, 1984; Grijspoor and Verstraete, 1997; Jenne et al., 2006), on activated sludge settling. In an effort to achieve ideal floc morphology for better settling, aerobic granular sludge (AGS) technology was developed in sequencing batch reactor systems (Morgenroth et al., 1997). AGS has been proven to be effective in enhancing settling velocities (Nor Anuar et al., 2007) and providing phosphorus removal (Cassidy and Belia, 2005). Also, the negative effects of excessive filamentous bacteria content on settling are particularly well documented (reviewed in Jenkins et al., 2003 and Martins et al., 2004).

Biomass density (defined here in the classical sense of mass per volume of biomass, not including voids) has received much less attention, although the gravitational force that drives sedimentation is a linear function of the difference between biomass density and the density of surrounding fluid (commonly termed the buoyant density), according to Archimedes principle. Density effects on solids settling have only recently been studied in detail, possibly because activated sludge density has generally been assumed to be relatively constant (e.g., Tchobanoglous et al., 2003). However, recent research has demonstrated this assumption is incorrect: for example, biomass densities were demonstrated to vary from 1.02 to 1.06 g/mL in samples from full scale wastewater treatment systems (Schuler and Jang, 2007a), indicating the sedimentation driving force varied by a factor of 3 in this data set (buoyant density ranged from 0.02 to 0.06 g/mL). Similarly, density varied from 1.02 to 1.04 g/mL in another full scale system data set (Dammel and Schroeder, 1991), and from 1.015 to 1.055 in samples from bench scale sequencing batch reactors (Schuler et al., 2001). This variability in density has been demonstrated to significantly affect settleability in both bench and full scale systems, and this effect was greatest in systems with at least moderate filament contents, as measured by the commonly-used sludge volume index (SVI) parameter (Schuler and Jang, 2007a,c). Increasing density also increases zone settling velocities, an alternative measure of settleability (Schuler and Jang, 2007b). Major factors demonstrated to affect density include polyphosphate content, which can vary with enhanced biological phosphorus removal (EBPR) activity, the related parameter non-volatile suspended solids (NVSS) content, and the operational parameter solids residence time (SRT) (Schuler et al., 2001; Schuler and Jang, 2007a).

Integrated fixed-film activated sludge (IFAS) is an increasingly popular modification of conventional activated sludge, in which solid media (typically suspended plastic pieces or fixed synthetic mesh) are added to suspended growth reactors to provide attachment surfaces for biofilms, thereby increasing microbial concentrations and rates of contaminant degradation. IFAS is an attractive option for retrofitting many existing facilities, in part because the inclusion of an attached biomass phase enriches for the slow growing autotrophs responsible for ammonia and nitrate oxidation (nitrifying bacteria), which are central to nitrogen removal processes in wastewater treatment, thus providing improved nitrification capacity without construction of new reactors (Randall and Sen, 1996).

Data on the effects of IFAS systems on biomass settleability are scarce and inconsistent. McQuarrie et al. (2004) reported lower SVI values, indicating improved settling, after addition of IFAS media to a full scale EBPR system (median values decreased from about 150 to about 135 mL/g). In contrast, Stricker et al. (2007) reported higher SVI values in a full scale IFAS system (median SVI = 113 mL/g) relative to a parallel non-IFAS system (median SVI = 86 mL/g). Sriwiriyarat et al. (2008) reported no significant difference in the average SVI values of parallel pilot scale systems with and without IFAS (both were poorly settling systems with average SVI values > 250 mL/g).

Given the importance of settling to activated sludge performance, the increasing use of IFAS systems, and uncertainties about IFAS effects on settleability, there is a research need to determine the effects of IFAS systems on biomass settling. This study focused on settling in IFAS/EBPR systems in particular.

It was hypothesized that (1) inclusion of IFAS media affects biomass density in EBPR systems by altering the amount of polyphosphate stored in the suspended phase biomass, (2) the relatively high SRT occurring in attached growth will lead to increased density because of increased NVSS content, and (3) changes in density due to addition of IFAS are large enough to significantly affect settleability.

The objectives of this study were to determine how IFAS media installation affects biosolids settling characteristics, including effects on biomass density and parameters known to affect density. The research approach was to study settling and biomass characteristics in pilot and full-scale systems that included IFAS trains and independent, non-IFAS controls, including analyses of the biomass in the attached and suspended phases, to provide the first such direct comparisons and the first measurements of biomass densities of biomass (both suspended and attached) in IFAS systems.

2. Materials and methods

2.1. Pilot systems

Parallel pilot wastewater treatment systems were located at the South Durham Water Reclamation Facility (SDWRF) at Chapel Hill, North Carolina, with one train containing IFAS media and the other operated as a non-IFAS control. Both systems were operated in an anaerobic–anoxic–aerobic (A2O) configuration for enhanced biological phosphorus removal (EBPR), denitrification, and nitrification (Fig. 1), with primary effluent as feed. Each train included an anaerobic (0.68 m³), two anoxic (0.68 m³) each) and two aerobic (1.37 m³) reactors and a clarifier. Influent wastewater primary effluent pumped directly from the SDWRF. The flow rate (Q) was 18.0 ± 0.7 m³/d to each train, resulting in a total hydraulic residence time (HRT) of 6.4 ± 0.25 h. Internal recycle flows for denitrification were pumped from the final aerobic reactors to the first anoxic reactors, with flow rates of 3.8 to 4Q. Return activated sludge was pumped from the clarifier to the anaerobic reactor (flow rate = 0.8 to 0.9Q). IFAS media
(Bioportz®, Entex Technologies Inc., Chapel Hill, North Carolina) was included in the two aerobic reactors of IFAS train. Bioportz media consists of extruded high density polyethylene with a biologically active (internal to each piece) surface area of 576 m²/m³ bulk media. Bioportz media was included in the aerobic reactors at a 50% bulk media fill volume, providing 288 m² of media surface area/m³ reactor volume. The Control train was operated without IFAS media. Dissolved oxygen concentrations were maintained higher than 3 mg/L for both trains.

In the first phase of the study, both trains were operated with a suspended biomass solids retention time (SRT) of 8 days, which was calculated as the suspended phase biomass in the bioreactors (including a correction for the approximately 8% aerobic reactor volume displaced by Bioportz media, and omitting the clarifiers) divided by the biomass loss rates due to wasting from the recycled activated sludge line and solids in the clarifier effluent. After approximately 6 months of steady state operation, the suspended phase SRT was changed to 4 days for the second phase of the study for both systems by adjusting the amount of sludge wasted daily.

2.2. Full scale systems

The SDWRF, where the pilot systems were located, includes a 5-stage Bardenpho process for removal of COD, nitrogen and phosphorus. The average flow rate of mixed liquor suspended solids concentration was maintained higher than 3 mg/L for both trains. The SDWRF, where the pilot systems were located, includes a 5-stage Bardenpho process for removal of COD, nitrogen and phosphorus. The average flow rate was approximately 3.8 x 10^3 m³/day (10 MGD) during the period of sampling for this study (April to June 2008), and the system SRT was about 22 days. The T2 Osborne wastewater treatment plant (Greensboro, NC) is composed of 12 parallel treatment basins, with each basin partitioned into 9 reactors, of which the first three are anaerobic, and the last six are aerobic. The total influent flow of the plant was approximately 65 x 10^3 m³/day (17 MGD) during this study. One of the treatment trains in the T2 Osborne plant was converted to an IFAS system in April, 2008 by putting Anox-Kaldnes® K3 media (35% bulk volume fill) in the first 3 chambers of aerobic zone, which received flow of approximately 10 x 10^3 m³/d. The IFAS train was independent of the non-IFAS system, with separate secondary clarifiers and solids recycle. Average total and aerobic SRTs of IFAS train during sampling period (from December 2008 to January 2009) were 6.8 and 5.9 days, respectively, and 5.6 and 4.5 days for the non-IFAS system.

2.3. Analytical methods

The systems were monitored by at least weekly measurements of mixed liquor suspended solids, growth on the solid media, nitrate, nitrite, phosphate and ammonia. Total suspended solids (TSS) and volatile suspended solids (VSS) were by Standard Methods 2540B and 2540E, respectively, and nonvolatile suspended solids (NVSS) was calculated as the difference between TSS and VSS. Ammonia, nitrate, and nitrite were measured by reagent kits (Hach Inc., Methods 10031, 10206 and 10207, respectively). All nitrogen species concentrations are expressed as mg N/L. Attached biomass growth was quantified by collecting 10 media pieces from each IFAS reactor, draining entrapped water 15 to 20 minutes, and drying at 105 °C overnight. The weight of dried media and biomass was measured and noted (W1). Dried biomass on the media was then removed by thorough cleaning using a brush and tap water until there were no visual biomass remains. The clean media was dried again at 105 °C for 5 to 6 hours and weighed (W2), and the attached dried solids calculated as W1 – W2. Total and dissolved (soluble) phosphorus were by Standard Methods 4500B and 4500C, respectively. Non-soluble phosphorus (Pns), an indication of phosphorus contained in biosolids, including polyphosphate, was calculated as the difference between total and soluble phosphorus. Settleability was determined by the sludge volume index (SVI) test, which is the volume occupied per mass of solids after 30 min of settling, according to the diluted SVI protocol (Lee et al., 1983). Biomass density was determined by a recently introduced method where samples were briefly centrifuged in a series of solutions containing dilutions of Percoll solution (Amersham Life Sciences Inc., Arlington Heights, Illinois) with a range of densities, and the average biomass density was determined by its tendency to sink or float in each solution (Schuler and Jang, 2007a).

Morphological floc characteristics were determined using wet mount, phase contrast microscopy, with digital photographs taken at 100× magnification. Four to six representative fields were typically analyzed per sample. Filament content was evaluated according to the filament index (FI) scale (0: none, 1: few, 2: some, 3: common, 4: very common, 5: abundant, and 6: excessive) as described in Jenkins et al. (2003). Floc shape was evaluated qualitatively without quantitative labeling with the emphasis on roundness, openness, and porosity of flocs.
2.4. Statistical comparisons

The statistical significance of the differences between mean values was evaluated using a 2-tailed t-test assuming unequal variances between the data sets. The statistical significance of the linear correlations between two parameters was evaluated by calculating F statistics and alpha values.

3. Results and discussion

3.1. South Durham pilot performance

Both the IFAS and Control pilot systems demonstrated excellent COD and phosphorus removal during the entire study period (Table 1). About 90% of COD was removed at the 8 day SRT in both systems, with no significant differences between the two trains. Average effluent total phosphorus concentrations were less than 1 mg/L in both systems at the 8 day SRT, and the Control system showed a small, but significant advantage in performance (p < 0.05 for both total and soluble phosphorus). The IFAS system had lower effluent ammonia and higher effluent nitrate concentrations at the 8 day SRT than the Control system, indicating higher rates of nitrification in the IFAS system (IFAS effluent ammonia and nitrate concentrations were 3.6 ± 1.2, and 5.1 ± 1.2 mg/L, respectively, while they were 7.8 ± 1.2, and 1.8 ± 0.4 mg/L, respectively in the Control system). The effluent TSS concentrations in the IFAS and control systems were 8.0 ± 0.9 mg/L and 7.9 ± 0.6 mg/L, respectively, which were not statistically different.

When the SRTs of both systems were decreased to 4 days, suspended phase TSS (mixed liquor suspended solids) decreased from 2,690 ± 100 to 1,740 ± 20, and from 2,760 ± 90 to 1,780 ± 40 mg/L in the IFAS and Control systems, respectively. The effluent TSS concentrations improved to 4.9 ± 0.2 and 4.5 ± 0.3 mg/L in the IFAS and Control systems, respectively, which was a small but statistically significant (p < 0.05) difference. Effluent COD was nearly unchanged in the IFAS system, but it increased 5.9 mg/L to 49.5 ± 4.9 mg/L in the Control system after the SRT decrease (Table 1). Effluent dissolved phosphorus concentrations increased from 0.57 ± 0.17 to 1.02 ± 0.11 mg/L in the IFAS system, and from 0.43 ± 0.11 to 1.25 ± 0.14 mg/L in the Control, suggesting some deterioration of phosphorus removal in both systems, and the differences between the two systems were statistically significant (p < 0.05) both before and after the change in SRT. Nitrification did not significantly change after the SRT decrease in the IFAS system in terms of effluent ammonia and nitrate concentrations. Nitrification performance deteriorated in the Control train, however, with effluent ammonia increasing from 7.8 ± 1.2 to 10.7 ± 0.9 mg/L and effluent nitrate decreasing from 1.8 to 0.6 ± 0.1 mg/L.

3.2. Microscopic observations

All samples collected from the SDWRF and pilot systems had very low filament contents (Fig. 2), with FI index values of 1 to 2 on the 6-point filament index scale (Jenkins et al., 2003). Attached growth biomass sheared from the Bioportz media showed a relatively high number of higher life forms, such as stalk ciliated protozoa, which likely reflected the higher effective SRT for the attached growth phase (Johnson et al., 2004). The flocs from suspended IFAS phase were typically larger than those in the suspended phases from the Control train, although this was not quantified. Samples from SDWRF and the Control train generally appeared to have more open and porous structures than those from the suspended IFAS phase.

Samples from the TZO (full scale) plant also showed low filament content (FI = 1 or 2), with no observable differences between the IFAS and non-IFAS systems. Contrary to the pilot system, the TZO IFAS and non-IFAS systems did not show appreciable difference in floc shapes and size.

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3.3. Density and settleability

Average densities from the three biomass types (Control suspended growth, IFAS suspended growth, and IFAS attached growth) in each sample set (Pilot 8 day SRT, Pilot 4 day SRT, and the full scale TZO plant) are shown in Fig. 3. The TZO plant was operated at an SRT of approximately 6.8 and 5.6 days for the IFAS and non-IFAS systems, respectively, during the sampling period of this study. The attached phase consistently yielded the lowest densities, with the general trend Control suspended phase density > IFAS suspended phase density > IFAS attached phase density. Density was significantly higher in the Control systems than in either the IFAS suspended phases or the attached phases in all three
Density was significantly greater in the IFAS suspended phase than in the attached phase in the pilot 4 d SRT \((p < 0.05)\), but the differences between these phases was not significant in the pilot 8 d SRT samples \((p = 0.055)\) or the full scale TZO samples \((p = 0.13)\). Density ranged from 1.031 to 1.049 g/mL across all samples.

The relationships between density and settleability (as SVI) are shown in Fig. 4. The negative correlations between density and settling were significant \((p < 0.05)\) within each of the pilot-scale sample sets (8 day and 4 day SRTs, Fig. 4A), within the full scale TZO samples (Fig. 4B), and within the entire data set (Fig. 4C). SVI values were less than 125 mL/g in all measurements, indicating good settling in all sample sources (for reference, “bulking” sludge has been defined as occurring at SVI values greater than 150 mL/g; Jenkins et al., 2003). The SVI values of the Control system samples were significantly lower than those in the IFAS samples within each of the Pilot 8 day SRT, Pilot 4 day SRT, and Full Scale TZO sample sets (data not shown). As noted, filament contents were low in all samples, with filament index values determined to be 1 or 2; there was no significant relationship between filament index values and settling.

### 3.4 Factors affecting biomass density

The full scale SDWRF plant samples had the highest density and the lowest SVI values of all systems in this study (Fig. 4C), and the attached (biofilm) phases had the lowest densities (Fig. 3). The latter observation was surprising, since the relatively long SRT of the attached phase was expected to lead to higher NVSS content due to accumulation of nonvolatile materials and endogenous degradation of VSS (Ekama and Wentzel, 2004), while increasing NVSS content has been linked to higher density (Schuler and Jang, 2007a). The reasons for the relatively low density of the attached phase were revealed by a consideration of phosphorus content.

The relationship between biomass phosphorus content (as non-soluble phosphorus content, or \(P_{ns}/VSS\)) for all systems is shown in Fig. 5. Linear regression best fit lines are shown for all pilot scale data (4 day and 8 day SRTs) and for the full scale TZO data; both of these correlations were statistically significant \((p < 0.05)\). The correlation between \(P_{ns}/VSS\) and density was also significant across all samples, including the somewhat outlying South Durham full scale samples \((R^2 = 0.49, p < 0.05)\). The positive relationship between phosphorus content in EBPR and density is expected, since polyphosphate is known to be of greater density than typical bacterial biomass (Suresh et al., 1985; Schuler et al., 2001).

The attached phases in the three IFAS systems included in this study yielded the lowest phosphorus contents and densities across all samples (circled values, Fig. 5). Relatively low polyphosphate content in the attached biomass likely occurred because this phase does not experience the anaerobic/aerobic cycling requisite for enrichment of PAOs (Barnard, 1974), and so it is expected to comprised primarily of non-PAO heterotrophs and nitrifying bacteria. However, the attached phases demonstrated polyphosphate contents that

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Fig. 4 – The relationship between density and settleability in pilot (A) and full scale (B) systems with IFAS and with non-IFAS controls. Figure C shows the average values and standard deviations for each systems shown in A and B, with the addition of the non-IFAS, full scale South Durham (SD) plant data. Best fit linear regression lines are for all data shown in each figure.

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were higher than typical values from non-EBPR domestic wastewater treatment systems: for example, phosphorus comprises 1.5 to 2% of total suspended solids (TSS) in these systems (Tchobanoglous et al., 2003), and Schuler and Jang (2007a) reported average Pns/VSS value of 0.024 mg/mg from non-EBPR full scale plants. The values obtained in this study were greater than 0.03 mg/mg in all samples, which suggests that attachment and detachment of the suspended phase EBPR biomass likely had an important influence on the biofilm population compositions.

Density was also well-correlated with nonvolatile suspended solids (NVSS/VSS) contents within each data set (Fig. 6), which was consistent with previous results for non-IFAS systems (Schuler and Jang, 2007a). These correlations are expected in part because of the contribution of polyphosphate to NVSS.

3.5. Effects of SRT change

After the SRT was decreased from 8 days to 4 days in the pilot scale system, average density significantly increased in both the Control and IFAS suspended phases ($p < 0.05$), but the small increase in the attached phase density was not statistically significant (Table 2, Fig. 5). These increases in density were consistent with increases in biomass phosphorus content (Pns/VSS) after the SRT change (Table 2, Fig. 5). Increases in Pns/VSS after the SRT change were significant for the Control and IFAS suspended phases ($p < 0.05$), but not in the attached phase ($p = 0.18$), similar to the trends in biomass density. Increasing biomass phosphorus content with decreasing SRT is expected, since lower SRTs are linked lower reactor biomass concentrations, while the loading of influent phosphorus available for uptake and storage was unchanged (Table 1). Onnis-Hayden et al. (2008) suggested that IFAS installation could improve EBPR as it allows for a short SRT in the suspended growth, which favors biomass phosphorus accumulation. While polyphosphate storage in the biomass increased after the SRT was decreased, effluent dissolved phosphorus concentrations increased, more than doubling in both the Control and IFAS trains (Table 1). This may have been caused by the increases in phosphorus storage content in the suspended phases; that is, approaching maximum polyphosphate storage levels by PAOs may have limited phosphorus uptake kinetics, which could have deteriorated EBPR performance. The slightly worse EBPR performance in IFAS systems was also found by Sriwiriyarat and Randall (2005), who compared performance of IFAS systems in UCT/VIP configurations with and without IFAS media.

Notably, the pilot scale data sets at the 8 and 4 day SRTs demonstrated a more or less continuous linear relationship between Pns/VSS and density (Fig. 5), while the NVSS/VSS versus density relationships at these SRTs were nearly parallel, but offset from each other (Fig. 6). This suggests that changes in polyphosphate storage after the SRT change dominated effects on density, while changes in NVSS/VSS due to other SRT-influenced factors, such as endogenous decay of VSS (Ekama and Wentzel, 2004), had less of an effect on density.
3.6. Comparisons with previous studies

As noted, previous studies have yielded mixed results with respect to the effects of IFAS on settling, with IFAS systems related to, for example, improved (Broomfield, CO; McQuarrie et al., 2004), worsened (Ontario, Canada; Stricker et al., 2007), and no change (Pilot study in Thailand; Sriwiriyarat et al., 2008) biomass settleability. The current study evaluated settling under well-controlled conditions in parallel IFAS and non-IFAS pilot-scale EBPR systems with identical suspended phase SRTs, and also in parallel IFAS and non-IFAS full-scale EBPR systems. In these systems, there was a small but significant and consistent increase in SVI values in the IFAS values of all three systems. The observed trends were apparently linked to somewhat lower biomass densities in the IFAS systems, which were in turn due to lower polyphosphate storage in the IFAS biomass. The differences in SVI values were consistent with unpublished data from another full-scale EBPR system, where SVI values of parallel IFAS and non-IFAS systems were 106 ± 12 and 83 ± 13 mL/g, respectively (James River Wastewater Treatment Plant, Newport News, VA, private communication). Although this plant is not configured for EBPR, higher effluent total phosphorus concentrations were reported in the IFAS train, suggesting that a similar phenomenon of lower polyphosphate storage and lower density in the IFAS train may have been occurring in this system as in the systems analyzed in the current study. The reasons for slightly worse EBPR performance in this study may be simply be the increased nitrate recycle to the anaerobic reactor, which could lead to competition for volatile fatty acids in this reactor from denitrifying metabolisms. Effects of IFAS on EBPR warrant further study.

McQuarrie et al. (2004) reported lower effluent solids concentrations after IFAS was incorporated to a full scale system, but, as noted, effluent TSS concentrations were nearly the same in the IFAS and Control treatment trains in the current study. The improved effluent solids in the McQuarrie et al. study may have been linked to a decrease in the suspended phase biomass by about 33% after IFAS addition (possibly because of a change in the SRT, which was not provided), which would have reduced solids loading to the secondary clarifiers. In contrast, MLSS concentrations (and clarifier solids loadings) were nearly the same in the IFAS and Control systems in the current study. In addition, any improvements in effluent TSS due to changes in floc shape characteristics may have been somewhat counteracted by the slightly lower density of the biomass in the IFAS system, due to its slightly lower polyphosphate content. Regardless, effluent TSS concentrations were low in both the IFAS and Control systems (consistently < 9 mg TSS/L).

It is noted that even in the IFAS systems, settleability remained good in all samples analyzed in this study. Filament contents were very low, which likely contributed to the low SVI values, and so the current results do not provide information about possible effects of IFAS systems on filament content, other than the demonstration that the IFAS system did not increase filament content relative to the non-IFAS control. In addition, the current study focused on EBPR systems only. The effects of IFAS on settleability in non-EBPR systems and on filament content in systems with filamentous bulking should be the focus of future research.

4. Conclusions

Analyses of parallel IFAS and non-IFAS EBPR systems at the pilot and full scales demonstrated that attached growth in
IFAS EBPR systems tends to be lower density than suspended growth, due to lower amounts of polyphosphate storage. The IFAS systems demonstrated worse settling than the Control systems, although these differences were small and settling was considered good in all samples studied. These differences were likely because of the lower density of the IFAS systems, and this in turn appeared to be linked to the slightly worse EBPR performance of the IFAS systems and hence lower polyphosphate storage. In particular, the attached-growth biomass had relatively low polyphosphate contents and densities. This work suggests that optimization of EBPR process should be taken into consideration for good settling character in designing IFAS system. The potential effects of IFAS on settleability in non-EPBR systems, and on filament contents in systems with larger filament populations, should be the subject of future research.

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