Water Science & Technology | 71.4 | 2015

Practical experience with full-scale structured sheet media (SSM) integrated fixed-film activated sludge (IFAS) systems for nitrification

Hua Li, Jia Zhu, James J Flamming, Jack O'Connell and Michael Shrader

ABSTRACT

Many wastewater treatment plants in the USA, which were originally designed as secondary treatment systems with no or partial nitrification requirements, are facing increased flows, loads, and more stringent ammonia discharge limits. Plant expansion is often not cost-effective due to either high construction costs or lack of land. Under these circumstances, integrated fixed-film activated sludge (IFAS) systems using both suspended growth and biofilms that grow attached to a fixed plastic structured sheet media are found to be a viable solution for solving the challenges. Multiple plants have been retrofitted with such IFAS systems in the past few years. The system has proven to be efficient and reliable in achieving not only consistent nitrification, but also enhanced bio-chemical oxygen demand removal and sludge settling characteristics. This paper presents long-term practical experiences with the IFAS system design, operation and maintenance, and performance for three full-scale plants with distinct processes; that is, a trickling filter/solids contact process, a conventional plug flow activated sludge process and an extended aeration process.

Key words | biofilm, IFAS, integrated fixed-film activated sludge, nitrification, structured sheet media

Hua Li (corresponding author)
Jia Zhu
Brentwood Industries, Inc.,
610 Morgantown Road,
Reading, PA,
USA
E-mail: *lli@brentw.com*

James J Flamming
Fishbeck, Thompson, Carr and Huber, Inc.,
Grand Rapids, MI,
USA

Jack O'Connell
Tata and Howard, Inc.,
Marlborough, MA,
USA

Michael Shrader
Hanover Engineering Associates, Inc.,
Ephrata, PA,
USA

INTRODUCTION

Many wastewater treatment plants in the USA are facing increased flows, loads, and more stringent ammonia discharge limits. These plants were originally designed as secondary treatment systems with no or partial nitrification requirements. Plant expansion through new construction is often not cost-effective due to either high construction costs or lack of land. Under these circumstances, integrated fixed-film activated sludge (IFAS) systems that use both suspended growth and biofilms grown on the surface of a plastic support media have been found to be a viable solution for solving the challenges.

Media used in IFAS systems include free-floating moving-bed bioreactor (MBBR) media and fixed-bed media. Studies on IFAS systems with MBBR media have been reported by various researchers such as Stricker *et al.* (2009); Rosso *et al.* (2011) and Di Trapani *et al.* (2013), etc. Data indicate that full-scale IFAS MBBR systems can improve performance when activated sludge systems are limited by sludge retention time (SRT). Studies on IFAS systems with fixed-bed media have also been reported by various researchers such as Lessel (1991, 1994); Muller (1998); Schlegel & Koeser (2007) and others. Seven full-scale IFAS plants utilizing several different fixed biofilm carriers were reported to have been in operation in Germany since the early 1980s (Muller 1998). The so-called Bio-2-Sludge system successfully improved carbon removal and nitrification efficiencies without new reactor construction for most of those plants. Suspended sludge of higher density, lower sludge index, and therefore better settling characteristics, was reported to have resulted from the installation of the IFAS systems. The sludge bulking issues that some of the plants had before the IFAS installation were solved. Mixed liquor suspended solid (MLSS) concentrations more than three times higher than before were achieved in certain plants (Muller 1998).

In the USA, full-scale and bench-scale evaluations of similar systems with rope and knit web-like fabric media were reported by various researchers such as Randall & Sen (1996); Jones *et al.* (1998) and Liubicich *et al.* (2004). While initial results similar to those provided by the German researchers were reported, long-term operational and performance data from full-scale plants and design

doi: 10.2166/wst.2014.397

information have been scarce. In addition, red worms (such as Chironomid larvae and/or *Tubifex*) have been reported for certain types of media to be a potential issue that affects consistent nitrification performance.

While testing a pilot IFAS system with a hybrid media (where PVC structured sheet media (SSM) was used to support the flexible fabric media in a sandwich pattern), Ye *et al.* (2009) discovered that red worms grew mostly on the fabric media but rarely on the SSM. This led to the development of the new SSM IFAS system. Multiple plants have been retrofitted with such systems in the past few years to meet stringent ammonia limits (Ye *et al.* 2010a; Flamming *et al.* 2011; Zhu *et al.* 2012). The system has proven to be efficient and reliable in achieving not only consistent nitrification (even under cold weather conditions) but also enhanced biochemical oxygen demand (BOD) removal and sludge settling characteristics. It also has the benefits of being simple and easy to operate and maintain, and has little or no operational complexity. This paper presents the long-term experience with the IFAS system design, operation and maintenance, and performance of three full-scale plants, that is, Coldwater, MI; Hopedale, MA; and Cocalico Valley Poultry Farms (CVPF), PA. Plant background information is shown in Table 1.

MATERIALS AND METHODS

Plant information

The three plants were facing similar challenges before the IFAS upgrade. They were not able to meet the new ammonia limits due to either cold weather conditions or shock loadings. In addition, they either lacked the land needed for constructing new tanks, or it was concluded that the construction of new tanks was not cost-effective.

System configuration and design

The SSM IFAS system consists of individual media towers. Each tower comprises multiple individual media modules. The modules are made of corrugated PVC sheets. The length and width of the towers can be flexible depending on the tank geometry. The height of the tower varies

Table 1 | Summary of three WWTPs

Name		Coldwater WWTP	Hopedale WWTP	Cocalico Valley Poultry Farms WWTP
Plant location		Coldwater, MI	Hopedale, MA	Stevens, PA
Design flow, ADF, m^3/day		12,112	2,226	75.7
Design peak flow, m^3/day		30,280	7,950	151.4
Wastewater type		Municipal with industrial component	Municipal	Industrial, poultry
Process description		TF/SC process with primary and secondary clarifiers	Plug flow AS with primary and secondary clarifiers	Extended aeration with three aeration tanks in series and secondary clarifiers
Wastewater temp, °C, mean ± standard deviation (Std.)		14.5 ± 3.1	16.0 ± 3.6	6–25 (design)
pH, mean ± Std.		7.6 ± 0.3	7.5 ± 0.3	6.9 ± 0.2
Plant influent BOD, mg/L, mean ± Std.		120.0 ± 55.7	271.7 ± 116.8	670.8 ± 118.6
Plant influent TKN mg/L, mean ± Std.		Not available	Not available	113.8 ± 22.3
Plant influent NH_3-N mg/L, mean ± Std.		20.8 ± 18.3	30.1 ± 9.9 (Primary effluent)	100.0 (design)
IFAS plant discharge limit	BOD (mg/L)	20.0	20.0	25.0
	TSS (mg/L)	30.0	30.0	30.0
	NH_3-N (mg/L)	2.0 (May 1 – Nov 30) 12.0 (Dec 1 – Mar 31) 10.0 (Apr 1 – Apr 30)	5.0 (May 1 – May 31) 11.0 (Nov 1 – Apr 30) 2.0 (Jun 1 – Oct 31)	4.0
	TN (mg/L)	No limit	No limit	No limit

depending on the side water depth of the aeration tank as room has to be reserved above the tower top for free board and beneath the tower bottom for diffuser installation. The number of towers needed for a specific project is determined based on the design organic and ammonia loading rates. Once the number of towers is determined, towers are installed in the aeration basin with a gap between adjacent towers. This gap, also called a downcomer region, leaves room for the flow coming out of the top of the media tower to go back down to the bottom of the media tower to allow recirculation, which acts as an airlift pump (Figure 1). In addition, it also provides room for diffuser maintenance. The airlift pump mechanism induces a rising vertical liquid velocity between 3.0 and 9.0 cm/s (Ye *et al.* 2010b). The airlift pump, together with the turbulence it provides, is critical for the IFAS system to control the biofilm thickness, and to maintain high biofilm respiration rate and nitrification performance as higher turbulence has been found to result in higher ammonia flux and higher areal biofilm density (Kugaprasatham *et al.* 1992).

Both cross-flow media (XFM) and vertical flow media (VFM) with specially designed air/flow distribution media (DM) have been used in these applications (Table 2). The DM is a proprietary media product that can distribute the air and water plume wider than an XFM module of the same size. It uses XFM modules as a base and has a flat sheet added between each two adjacent corrugated sheets. It provides uniform air/water distribution to the overlaying VFM modules with fewer diffusers. As a newer generation of media configuration, the combination of VFM and DM has more specific surface area (SSA) than XFM only. It also enhances the airlift pump effect and results in better biofilm thickness control. Support of the media towers can be either permanent support using a grating and pier system anchored to the floor of the aeration basin or a detachable frame support system that can be lifted out of the basin as a whole unit. Fine bubble diffusers are normally used for providing better oxygen transfer efficiencies and biofilm thickness control.

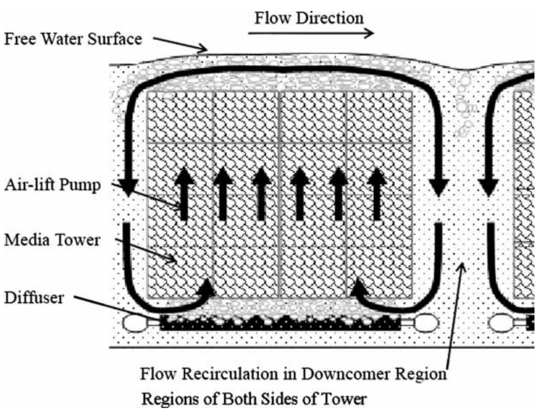

Figure 1 | Schematic of media tower configuration and airlift pump.

Table 2 | Summary of media information

Plant name	Coldwater WWTP	Hopedale WWTP	CVPF WWTP
IFAS data period	Aug. 2010 – Mar. 2013	Aug. 2009 – Dec. 2012	June 2010 – Nov. 2013
Media location	Solids contact basins	Aeration basins, towards the back of the tank	Aeration basins
Media type	XFM	XFM	VFM/DM
Media fill percentage, %	60	25	41
Media SSA, m^2/m^3	157	157	275/131

Plant operational and performance data were collected and analyzed. The effects of operational and environmental parameters on nitrification performance were also studied and discussed. With an IFAS system, it is difficult to quantify the respective nitrification contribution from the biofilm and suspended biomass without advanced analytical techniques. The nitrification rates, therefore, will be evaluated based on either the concentration of the mixed liquor volatile suspended solids (MLVSS, suspended biomass only in this paper) or the surface area of the media. As a result, the specific nitrification contribution of each kind of biomass was unfortunately not considered, even though it could have been done by measuring the ammonia uptake rate/oxygen uptake rate and determining the nitrification capacity of the suspended biomass.

RESULTS AND DISCUSSION

Coldwater, MI

The actual influent ammonia concentration to the solids contact basin at the Coldwater WWTP ranged from 1.3 to 88.0 mg/L (average 11.4 mg/L, Std. 10.8). The average hydraulic retention time (HRT) of the solids contact basin was 3.3 h. Additional information regarding the plant can be found in Flamming *et al.* (2011). A comparison of the nitrification rates in the solids contact basin before and after the

IFAS installation indicates that the IFAS system significantly improved the nitrification performance consistency at loading rates between 0 to 60 g NH_3-N/kg MLVSS-day (Figure 2, left). When the loading rates exceeded 60 g NH_3-N/kg MLVSS-day (between 60 and 210) with highly variable influent ammonia concentrations, the nitrification rates of the IFAS system appeared to be significantly better than that of the AS system. The higher the loading rate, the more pronounced the performance of the IFAS system was over the AS system. The IFAS system demonstrated very high nitrification capacity potential at higher loading rates.

The nitrification rates in terms of media surface area (Figure 2, right) indicate that the system performed consistently to a surface loading rate up to 2.0 g NH_3-N/m^2-day. The performance started to scatter when the loading rate was higher. The scattering in data may have been partly caused by the highly variable influent ammonia concentrations from the industrial component. The varying TF effluent BOD concentration (average 37.6 mg/L, Std. 17.8) going into the solids contact basin may have also affected the nitrification performance consistency at higher ammonia loading rates.

In addition to the improvement in nitrification, the overall effluent quality was significantly improved compared to that of the previous AS system. The effluent BOD concentration was below 10 mg/L 98.4% of the time (average 2.6). The effluent total suspended solids (TSS) concentration was under 10 mg/L 84% of the time and 20 mg/L 97.7% of the time (average 8.3).

Hopedale, MA

The ammonia concentration entering the Hopedale wastewater treatment plant (WWTP) aeration tank ranged from 16.5 to 48.0 mg/L (average 30.1 mg/L, Std. 9.9) based on record data. The average HRT for the aeration tank was 11.8 h. The average HRT for the portion of the aeration tank where media were installed was 7.4 h. The actual average BOD concentration entering the aeration tank was 121.2 mg/L (Std. 57.4). The soluble BOD was assumed to have been removed before reaching the first media tower. The ammonia removed through nutrition uptake was accounted for in the nitrification rate calculation. Other background information can be found in Ye et al. (2010a).

The nitrification rates (Figure 3, left) indicate that the IFAS system performed consistently well with loading rates between 0 and 190.0 g NH_3-N/kg MLVSS-day in terms of suspended MLVSS when the temperature was higher than 11 °C. These nitrification rates are significantly higher than the normal design rates for a conventional AS system. This is probably a direct consequence of the sum of the contribution to nitrification due to both kinds of biomass. When the wastewater temperature was lower (i.e., between 8 and 11 °C), the nitrification rates were found to be consistent at various loading rates even though lower rates were observed.

The nitrification rates based on media surface area were between 0.5 and 4.5 g NH_3-N/m^2-day (Figure 3, right). The system provided consistent nitrification for both high and low temperatures. The lower variation of influent ammonia loadings, relatively longer HRT and therefore more contact time with media may have contributed to the system's overall performance consistency. Schlegel & Koeser (2007) recommended a total Kjeldahl nitrogen (TKN) surface loading rate of less than 2.0 g/m^2-day for tertiary nitrification to achieve a high removal of ammonia-nitrogen for a pure fixed-bed biofilm system. The ammonia loading and

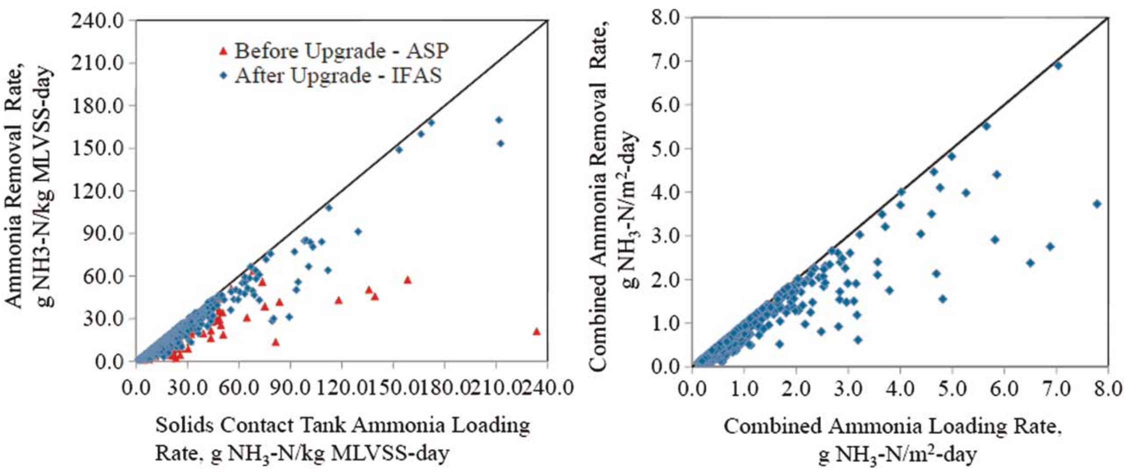

Figure 2 | Coldwater, MI. Left: IFAS system ammonia loading rates vs removal rates based on suspended MLVSS concentration. Right: IFAS ammonia media surface loading rate vs removal rate.

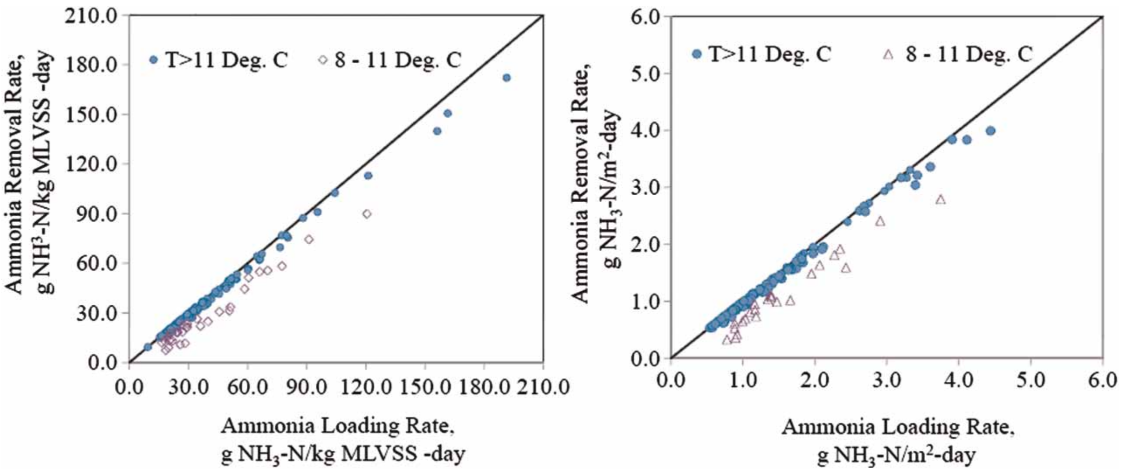

Figure 3 | Hopedale, MA. Left: IFAS system ammonia loading rate vs removal rate based on suspended MLVSS concentration. Right: IFAS system ammonia media surface loading rate vs removal rate.

nitrification rates for an IFAS system are expected to be higher than those for a pure fixed-bed biofilm system as both the suspended biomass and biofilm can contribute to nitrification performance.

Overall, the effluent quality was significantly improved by the IFAS system upgrade. The maximum effluent BOD concentration was 10.3 mg/L (average 2.6). The maximum effluent TSS concentration was 11.5 mg/L (average 4.3).

Table 3 | Summary of plant performance before and after IFAS installation

Year	Max. Eff. NH_3-N concentration	Year	Max. Eff. NH_3-N concentration
2006	20.6	2010[a]	10.9/1.63
2007	23.8	2011	1.65
2008	13.4	2012	2.82
2009	8.26	2013[b]	2.87

[a]Before/after IFAS upgrade.
[b]Based on data through Nov. 2013.

Cocalico Valley Poultry Farms, PA

The CVPF WWTP was an extended aeration process with two process trains. Each train had three identical aeration basins. The average wastewater temperature in winter was 8.4 °C and daily temperature was as low as 5.3 °C. One media tower was installed in each of the 6 aeration basins. The design organic loading rate in terms of media surface area was 8.2 g BOD/m^2-day for the entire plant and 42.4 g BOD/m^2-day for the first tank; the TKN loading rate was 0.68 g TKN/m^2-day for the entire plant and 3.54 g TKN/m^2-day for the first aeration tank. The organic loading rate in terms of MLSS (design 3,000 mg/L) was 0.25 g BOD/g MLSS-day for the entire plant and 0.75 g BOD/g MLSS-day for the first aeration tank; the TKN loading rate was 20.7 g TKN/kg MLSS-day and 62.1 g TKN/kg MLSS-day. Additional information regarding the plant can be found in Zhu *et al.* (2012). According to the maximum effluent ammonia concentrations from 2006 to 2013 (Table 3), the IFAS upgrade in 2010 successfully and consistently brought the effluent ammonia concentration into compliance.

One additional interesting phenomenon worth noting at this plant is total nitrogen removal under aerobic conditions. Based on multiple sampling data points from different sampling events, 85 to 90% of the soluble chemical oxygen demand (SCOD) was removed in the first aeration tank, where a significant amount of TN was also removed. The amount of total nitrogen (TN) removed appears to be linearly proportional to the amount of SCOD removed, which suggests that part of the SCOD removed was due to simultaneous nitrification and denitrification (SND) (Zhu *et al.* 2012). SND has been reported in fixed media systems by various researchers (e.g., Randall & Sen 1996; Muller 1998; Hibiya *et al.* 2003 and Li *et al.* 2013). The low dissolved oxygen concentration (0.15–1.1 mg/L) in the first aeration tank may have encouraged SND. Pilot results (to be published) show that nitrification rates are relatively low at the front of a plug flow aerobic reactor where the organic loading is higher and increase towards the back of the reactor where organic loading is lower. With soluble COD loadings between 30–50 g COD/m^2-day, the ammonia flux rate can be 0.4–0.8 g NH_3-N/m^2-day (20 °C). This nitrification capability is believed to be critical in supporting the observed SND in the fixed-bed IFAS system.

Sludge volume index, MLSS and suspended SRT

Fixed-bed IFAS systems tend to produce sludge that differs considerably from that of more usual AS processes (Muller 1998). The sludge from the IFAS sytem tends to have a lower organic fraction, higher density, and lower sludge volume index (SVI). The installation of the IFAS systems at the three plants seemed to have produced sludge with such characteristics. At Coldwater, the solids contact basin had occasional bulking issues before the IFAS upgrade. The 90 percentile SVI number before the IFAS upgrade was approximately 360 ml/g. After the IFAS upgrade, sludge bulking rarely occurred. The 90 percentile SVI number was approximately 260 ml/g. Significant improvement on SVIs was observed at Hopedale. Before the IFAS upgrade, data from 2007 indicate there was often bulking in the plant with a 90 percentile SVI number being 280 ml/g. After the IFAS upgrade, sludge bulking has been rare. The 90 percentile SVI number since the upgrade was approximately 160 ml/g between July 2009 and September 2012.

Improvement on SVIs by the SSM IFAS systems enabled the systems to operate at higher MLSS concentrations. Typical MLSS concentration at Coldwater before the upgrade averaged at 3,600 mg/L from April 2008 to April 2010 with a maximum observed concentration of 4,653 mg/L. The MLSS concentration after the IFAS upgrade averaged 4,690 mg/L from May 2010 to January 2013 with a maximum observed concentration of 9,579 mg/L. This improved the average suspended SRT from 3.8 days to 9.1 days. At Hopedale, sludge bulking before the IFAS upgrade happened often in winter time when the wastewater temperature was close to or below 10 °C. The bulking sludge resulted in washout of MLSS from the aeration tank. MLSS concentration as low as 132 mg/L was recorded. This washout of bacteria significantly affected the performance of the plant. The SSM IFAS system improved the system in two ways. First, it provided carrier for biofilm growth, which is resistant to washout. Second, it improved the SVIs of the suspended growth, enabling the system to maintain a relatively high suspended MLSS concentration for treatment. The suspended MLSS concentration of the IFAS system has rarely dropped below 800 mg/L since the upgrade. With the attached biofilm and improved suspended biomass concentration (suspended SRT ranged from 2.1 to 27.7 days), the total system SRT was significantly improved, as was the nitrification performance. At the CVPF plant, the MLSS concentration in the first aeration tank has ranged from 6,000 to 9,000 mg/L due to excellent sludge settleability, which significantly raised the suspended SRT of the system and enhanced nitrification, especially during low temperature periods.

At Coldwater, the IFAS system reduced the sludge yield and sludge organic content. The average observed sludge yield dropped from 0.96 g TSS/g BOD for the TF/SC to 0.78 g TSS/g BOD for the TF/IFAS system. The average MLVSS/MLSS ratio was 0.59 for the TF/SC and 0.53 for the TF/IFAS system. The relatively higher observed sludge yield from the TF/SC process was believed to be a direct result of the TF. At Hopedale, the average observed sludge yield was estimated to be 0.60 g TSS/g BOD. Specific sludge yield for fixed-bed IFAS systems has been found to be lower than for conventional AS systems. In a similar IFAS plant in Germany, the sludge production diminished to about 50% of the original amount after the IFAS upgrade (Muller 1998). Part of the reason for the lower sludge yield and organic content may be a direct result of the increased SRT with which more substrates get oxidized and more bacteria experience elevated endogenous respiration and decay. Another reason for lower sludge yield and effluent TSS concentration may be due to grazing by higher animals because long retention time reactors and long-aged biofilms allow for the growth of such animals such as rotifers, lavae and other grazing macro-organisms (Canals *et al.* 2013).

Biofilm

The amount of biofilm and bacteria species that grow on the media is affected by the wastewater characteristics such as BOD and ammonia loadings, temperature and pH, etc. More growth on the media is expected at the front of the system where BOD loading is higher than at the end of the system where BOD loading is lower. While it is inconvenient to quantify the amount and thickness of biofilm on the media at these full-scale installations, one pilot study for a similar system (Ye *et al.* 2009) indicated that the average dry mass and biofilm thickness on the media of a similar IFAS system with typical municipal wastewater were up to 22.6 g/m^2 and 0.46 mm, respectively. A hypothesis is generally accepted for most fixed-bed IFAS systems that nitrifiers usually prefer to reside on the media, whereas heterotrophs would mostly reside in the mixed liquor. This hypothesis is supported by various research (e.g., Hibiya *et al.* 2003;

Onnis-Hayden *et al.* 2011). The presence of nitrifying biofilm on the media therefore functions to decouple the SRTs for the heterotrophs and nitrifiers. The co-existence of nitrifiers with heterotrophs at the front portion of an IFAS process where readily biodegradable BOD is available is believed to be an essential factor that leads to SND. Further research is underway to identify the abundance and distribution of key functional microbial populations, especially the nitrifier species and their activities in these systems utilizing 16S rRNA-targeted fluorescence in situ hybridization technology.

Operation and maintenance

The long-term operational experience with the three plants indicates that the operation of IFAS systems is similar to the operation of AS systems. It does not require more than an AS system requires for regular operational procedures. The media towers are fixed and submerged in the aeration tank. They do not normally need attention once the system is started up and operated as designed.

Fine screens with a maximum 6-mm opening size are recommended to prevent fibrous materials from entering the system and potentially plugging the media. The Coldwater plant was designed with a 6-mm band screen. The CVPF plant had only grease traps, which trap any grease and feathers from the plant washdown process. At Hopedale, there was a coarse bar screen with one-inch openings. During an inspection of the media in early 2013, accumulation of fibers was found at the interface of media modules. Therefore, having a fine screen is essential to the normal operation of fixed media systems.

Like all AS systems, fine bubble diffusers need to be inspected according to the manufacturer's recommendations. A uniform rolling pattern (Figure 1) is easily discernible when all diffusers are working properly. Broken diffusers will result in either a local turbulent water spring with high flows or a quiescent area on top of the media towers with no flows, both of which are easily identified through visual inspections. Replacement of malfunctioning diffusers in a timely manner is critical to the normal operation of the system just as it is to an AS system. Having malfunctioning diffusers for an extended period of time may result in degradation of system performance, possible media clogging by uncontrolled growth, and significant sludge deposition on the tank floor underneath the diffusers. Replacement of diffusers may require draining of the aeration tanks unless the diffusers are specially designed and can be taken from the water surface through threaded connections. Due to high groundwater levels, the Coldwater plant cannot easily drain the aeration tanks to inspect or maintain the diffusers. As such, the design incorporated ceramic diffusers with an in-situ hydrogen chloride cleaning system, which has proven highly successful in maintaining properly functioning diffusers.

The three IFAS systems did not result in apparent headlosses in the aeration tanks where they were installed and therefore did not necessitate any adjustment in the original plant hydraulic profile. The reason for the insignificant headloss is believed to be due to the relatively low forward velocity in the aeration tanks. In another full-scale plant where a Modified Ludzack Ettinger process with an internal mixed liquor return ratio of three was present, the headloss was also found to be insignificant.

CONCLUSIONS

1. The long-term performance data of the three plants prove that SSM IFAS systems are a viable solution for retrofitting under-designed AS systems (i.e., systems with shorter than required HRT/SRT for complete nitrification) without new construction to increase ammonia removal capacity and meet more stringent nitrification standards (even under cold weather conditions, i.e., 6–11 °C).
2. The SSM IFAS systems show the potential to nitrify consistently with an ammonia loading rate up to 150 g NH3-N/kg MLVSS-day in terms of MLVSS, or 4.0 g NH_3-N/m^2-day in terms of media surface area.
3. The IFAS system can significantly improve sludge settleability and reduce sludge yield with increased contact time between media and substrate. It also improves BOD and TSS removal efficiency.
4. Operation and maintenance of an SSM IFAS system is very similar to that of an AS process. Attention to the media is minimal when the required fine screens are installed and diffusers properly maintained.

ACKNOWLEDGEMENTS

The authors would like to extend their gratitude to Ken Webb, Superintendent at Hopedale WWTP; David Woodman, Superintendent at Coldwater WWTP; and John

McEwing, Operator at CVPF Plant for providing the plant operation and performance data.

REFERENCES

Canals, O., Salvadó, H., Auset, M., Hernández, C. & Malfeito, J. J. 2013 Microfauna communities as performance indicators for an A/O shortcut biological nitrogen removal moving-bed biofilm reactor. *Water Res.* **47** (9), 3141–3150.

Di Trapani, D., Christensson, M., Torregrossaa, M., Viviani, G. & Ødegaard, H. 2013 Performance of a hybrid activated sludge/biofilm process for wastewater treatment in a cold climate region: Influence of operating conditions. *Biochem. Eng. J.* **77**, 214–219.

Flamming, J. J., Woodman, D. L. & Kulick, F. M. 2011 Application of structured sheet media IFAS for ammonia polishing from a trickling filter solids contact process. *Proceedings of the 84th Annual Conference and Exposition (WEFTEC 2011)*, Los Angeles, California, USA, 15–19 October 2011.

Hibiya, K., Terada, A., Tsuneda, S. & Hirata, A. 2003 Simultaneous nitrification and denitrification by controlling vertical and horizontal microenvironment in a membrane-aerated biofilm reactor. *J. Biotechnol.* **100** (1), 23–32.

Jones, R. M., Sen, D. & Lambert, R. 1998 Full-scale evaluation of nitrification performance in an integrated fixed-film activated sludge process. *Water Sci. Tech.* **38** (1), 71–78.

Kugaprasatham, S., Nagaoka, H. & Ohgaki, S. 1992 Effect of turbulence on nitrifying biofilms at non-limiting substrate conditions. *Water Res.* **26**, 1629–1638.

Lessel, T. H. 1991 First practical experience with submerged rope type (ringlace) biofilm reactors for upgrading and nitrification. *Water Sci. Tech.* **23** (2), 825–834.

Lessel, T. H. 1994 Upgrading and nitrification by submerged biofilm reactors, experience from a large scale plant. *Water Sci. Tech.* **29** (10/11), 167–174.

Li, H., Zhu, J., Kulick III, F. M., Koch, K. & Rothermel, B. 2013 Submerged structured sheet media (SSM) IFAS and SSM fixed-film only systems for simultaneous carbon oxidation, nitrification and denitrification and implications. *Online Proc. of the 86th Annual Conference and Exposition (WEFTEC 2013)*, Chicago, IL, USA, 7–9 October 2013.

Liubicich, J., Pitt, P., Psaltakis, E., Zabinski, A. & Lauro, T. 2004 Bench-scale testing of the IFAS technology at the Mamaroneck WWTP. *Proceedings of the 77th Annual Conference and Exposition (WEFTEC 2004)*, New Orleans, Louisiana, USA, 2–6 October 2004.

Muller, N. 1998 Implementing biofilm carriers into activated sludge process – 15 years of experience. *Water Sci. Tech.* **37** (9), 167–174.

Onnis-Hayden, A., Majed, N., Schramm, A. & Gu, A. Z. 2011 Process optimization by decoupled control of key microbial populations: Distribution of activity and abundance of polyphosphate-accumulating organisms and nitrifying populations in a full-scale IFAS-EBPR plant. *Water Res.* **45**, 3845–3854.

Randall, C. W. & Sen, D. 1996 Full-scale evaluation of an integrated fixed-film activated sludge (IFAS) process for enhanced nitrogen removal. *Water Sci. Tech.* **33** (12), 155–162.

Rosso, D., Lothman, S., Jeung, M. K., Pitt, P., Gellner, W. J., Stone, A. L. & Howard, D. 2011 Oxygen transfer and uptake, nutrient removal, and energy footprint of parallel full-scale IFAS and activated sludge processes. *Water Res.* **45** (18), 5987–5996.

Schlegel, S. & Koeser, H. 2007 Wastewater treatment with submerged fixed bed biofilm reactor systems – design rules, operating experiences and ongoing developments. *Water Sci. Tech.* **55** (8–9), 83–89.

Stricker, A. E., Barrie, A., Maas, C. L. A., Fernandes, W. & Lishman, L. 2009 Comparison of performance and operation of side-by-side integrated fixed-film and conventional activated sludge processes at demonstration scale. *Water Environ. Res.* **81**, 219.

Ye, J., McDowell, C. S., Kulick, F. M., Koch, K. & Rothermel, B. 2009 Pilot testing of structured sheet media for wastewater biological nutrient removal. *Proceedings of the 82nd Annual Conference and Exposition (WEFTEC 2009)*, Orlando, FL, USA, 10–14 October 2009.

Ye, J., Chestna, K., Kulick, F. M. & Rothermel, B. C. 2010a Full scale implementation, performance, and operation of a structured sheet media IFAS system. *Proceedings of the 83rd Annual Conference and Exposition (WEFTEC 2010)*, New Orleans, LA, USA, 2–6 October 2010.

Ye, J., Kulick, F. M. & McDowell, C. S. 2010b Effective biofilm control on high surface density vertical-flow structured sheet media for submerged applications. *Proceedings of the 83rd Annual Conference and Exposition (WEFTEC 2010)*, New Orleans, Louisiana, USA, 2–6 October 2010.

Zhu, J., Li, H., Kulick, F. M. & Koch, K. 2012 Performance of a structured sheet media (SSM) IFAS system for poultry wastewater treatment – a case study. *Online Proceedings of the 85th Annual Conference and Exposition (WEFTEC 2012)*, New Orleans, Louisiana, USA, 1–4 October 2012.

First received 26 June 2014; accepted in revised form 3 September 2014. Available online 17 September 2014