

# **Biofilm Performance of High Surface Area Density Vertical-Flow Structured Sheet Media for IFAS and Fixed Bed Biofilm Reactor (FBBR) Applications**

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## **ABSTRACT**

PVC structured sheet media has recently received increasing attention as a cost-effective alternative for IFAS applications. However, the impact of its type and configuration on the process performance has been less studied. This study was conducted to evaluate the biofilm performance of a high surface area density Vertical-Flow (VF) media in conjunction with a proprietary distribution media for IFAS and Fixed-Bed Biofilm reactor (FBBR) applications.

The study demonstrated that the VF media combined with the proprietary distribution media is capable of achieving complete nitrification and high-rate BOD removal for both IFAS and FBBR applications. As an essential element in the VF media system, the distribution media not only maximized the air and wastewater distribution over the entire surface area of the media, but also optimized the airlift pumping through the VF media for sufficient mixing and effective biomass control. Favorable kinetic rates (e.g. tertiary ammonia rates up to 1.4 g NH<sub>3</sub>-N/m<sup>2</sup>-day at 15°C, SCOD removal rate of 30 g SCOD/m<sup>2</sup>-day at a SCOD load of 45 g SCOD/m<sup>2</sup>-day, and pre-denitrification rates of 1.0-2.0 g NO<sub>3</sub>-N/m<sup>2</sup>-day) have been consistently observed in the VF structured sheet media system, mainly due to the intimate contact between thin biofilm and substrates/oxygen as promoted by the dedicated aeration associated with the media towers.

Compared to cross-flow (CF) media, the VF media provides an enhanced air/wastewater distribution and also offers significantly higher treatment capacity per unit media volume due to the increased specific surface area (e.g. 96 ft<sup>2</sup>/ft<sup>3</sup> or 315 m<sup>2</sup>/m<sup>3</sup>) and comparable kinetic rates (e.g. concurrent 0.65 and 5.5 g/m<sup>2</sup>-day ammonia and soluble COD removal, respectively) in the IFAS application. Comparison of the VF media with other media systems (e.g. free-floating media and fabric media) is also discussed in the paper.

## **KEYWORDS**

Structured Sheet Media, Vertical-Flow Media, Integrated Fixed-Film Activated Sludge (IFAS), Fixed-Bed Biofilm Reactor (FBBR), Biological Nutrient Removal (BNR), Nitrification, BOD Removal, Denitrification, Simultaneous Nitrification and Denitrification (SND)

## INTRODUCTION

PVC structured sheet media has been widely used in trickling filter applications for attached biomass growth since the late 1950's (Bryan, 1982). Submerged applications with structured sheet media, such as Submerged Aerated Filters (SAFs), have also been common in package wastewater treatment plants. Table 1 lists some examples of structured sheet media SAFs on the market. More recently, the use of structured sheet media in the Integrated Fixed-film Activated Sludge (IFAS) (Ye et al., 2009, 2010a) and Submerged Fixed Film (SFF) or Fixed Bed Biofilm Reactor (FBBR) (McDowell and Hubbell, 2000) processes have been increasingly recognized as a cost-effective alternative for full-scale municipal wastewater biological treatment due to enhanced performance, improved process stability, simple installation, and low maintenance and operational requirements.

Table 1 Examples of structured sheet media SAFs on the market

Process	Manufacturer	Media Type	Typical Media Fill
FAST	Smith & Loveless (Lenexa, KS)	Cross-Flow (CF)	100%
Copa SAF	EIMCO Water Technologies (Austin, Texas)	Cross-Flow (CF)	100%
SAF	Severn Trent Water (Ft. Washington, PA)	Cross-Flow (CF)	100%
EnviroSAF	KEE Process Limited (UK)	Cross-Flow (CF)	100%

### Description of Structured Sheet Media Reactors for IFAS and FBBR Applications

Different from SAFs which are completely mixed reactors with a typical 100% media fill (Rusten, 1984), structured sheet media systems for aerobic IFAS and FBBR applications (Figure 1 (a)) are often installed as discrete towers along the direction of flow to approach a plug-flow configuration. Fine bubble diffusers are typically mounted beneath the media towers, but not in the downcomer region between media assemblies in order to facilitate mixed liquor circulation and mixing by the airlifting pumping through media. For anoxic or anaerobic applications with structured sheet media, the rolling-water circulation pattern is typically induced by draft tube mixers (Figure 1 (b)).

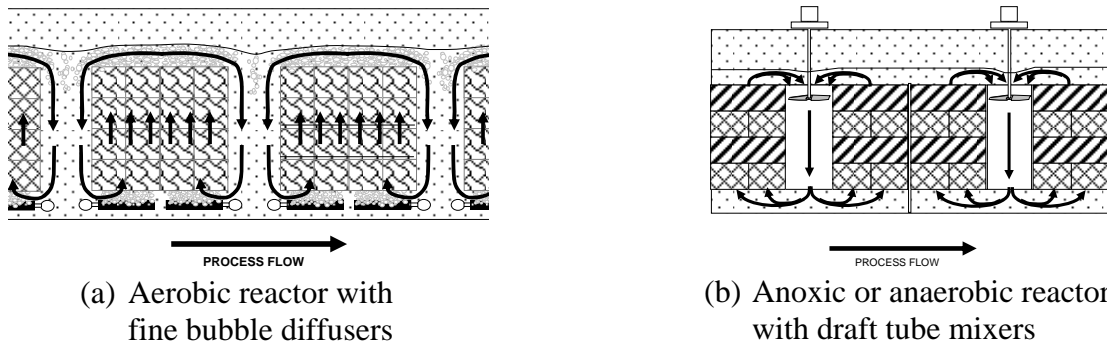


Figure 1 Schematics of rolling-water patterns in submerged structured sheet media systems

### Air/water Distribution over Submerged Structured Sheet Media

In trickling filters, a continuous and uniform horizontal distribution of wastewater over the structured sheet media is typically achieved by the proper design of distribution arms/nozzles

and also through the application of CF media for wastewater gravity redistribution. In contrast, the distribution of air and wastewater through submerged structured sheet media has to rely on the airlift pumping action as a result of the diffused air injected under the media. Due to the nature of the non-continuous diffuser coverage in practice and also the “necking effect” of rising air bubbles resulting from the compression of non-isolated surrounding water, the typical trickling filter CF media becomes less efficient for air and wastewater redistribution in submerged applications. It is therefore essential that a specific method, such as the proprietary distribution media used in this study, be applied to enhance flow distribution and mixing for a submerged process with structured sheet media.

### Objectives of the Study

The application of CF structured sheet media for a submerged system has been previously reported (Ye et al., 2009); however, different from trickling filters, the impact of other types and configurations of the structured sheet media on the process performance has not been studied for submerged applications. In this study, a newly developed distribution media was used in order to maximize air/water distribution through structured sheet media for submerged applications. The primary objectives of the study were to observe the air and wastewater distribution pattern over the new distribution media and evaluate the biofilm performance of a high surface area density Vertical-Flow (VF) media in conjunction with the distribution media for IFAS and FBBR applications. The study was also intended to compare the performance between VF, CF, and other media and develop design criteria, such as nitrification and BOD removal rates, for the VF media system.

## METHODOLOGY

### Description of the Pilot Facility

Figure 2 is a simplified schematic of the pilot facility in an IFAS operating mode, which consists of one swing tank under anoxic condition as shown and two staged aeration tanks furnished with tubular fine bubble diffusers in a MLE process. Media fill fraction in each aerobic tank was approximately 46 % (by vol.) with one (1) 1.0-ft layer of distribution media module at the bottom and one (1) 2.0-ft layer of VF media module on the top. The swing tank can be operated as an anoxic reactor using a mixer or an aerobic reactor using coarse bubble diffusers. In FBBR operating modes with no RAS recycle, the swing tank was also filled with about 80% CF media in order to retain denitrification populations for nitrate removal with the MLE process. The influent to the pilot was supplied by a submersible pump placed in the effluent channel of a primary clarifier at the City of Reading, PA wastewater treatment plant. The treated wastewater and the Wasted Activated Sludge (WAS) were returned back to the plant headworks.

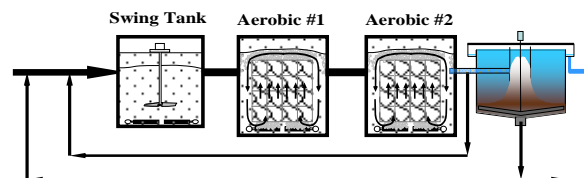


Figure 2 Simplified process schematic of the pilot facility in an IFAS operating mode

CF media was selected for anoxic operation in the swing tank due to its efficient wastewater re-distribution by providing necessary headloss for even distribution of flow when the system is in the absence of the diffused air and “necking effect”. The proprietary distribution media is originally derived from CF media, but has innovative features to minimize the “necking effect” and maximize air/water distribution through entire surface areas of the media modules. The VF structured sheet media was created by joining adjacent corrugated PVC sheets with solvent bonding and forming them into modules and has a specific surface area of 96 ft<sup>2</sup>/ft<sup>3</sup> (315 m<sup>2</sup>/m<sup>3</sup>) (Figure 3).

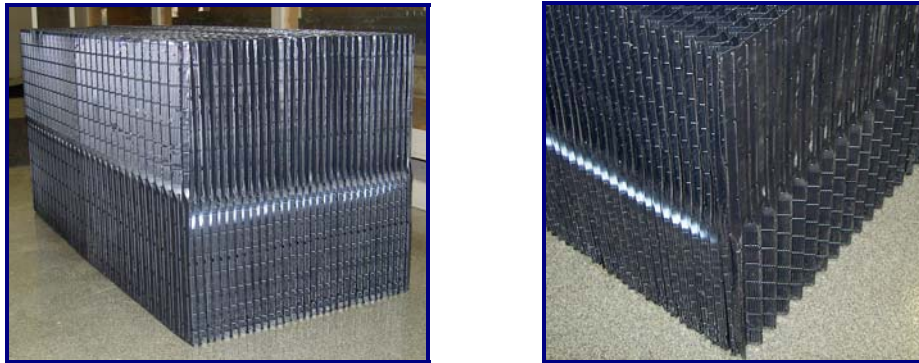


Figure 3 High surface area density VF structured sheet media

### Testing Phases of the Pilot Study

The pilot has been in operation for about one year, from April 2009 to March 2010. It was segmented into three testing phases, consisting of (1) IFAS MLE phase (Phase 1), (2) FBBR BOD roughing phase (Phase 2), and (3) FBBR MLE phase (Phase 3). Each testing phase lasted approximately four months. The design operating conditions of each testing phase are summarized in the Table 2.

Table 2 Design operating conditions of different testing phases in the pilot study

Parameters		Phase 1-IFAS MLE	Phase 2-FBBR Roughing	Phase 3-FBBR MLE
Testing period		4/2009-7/2009	8/2009-11/2009	12/2009-3/2010
Process		MLE	MLE	MLE
Flow rate, gpm		1.3	1.3	0.75
RAS/influent ratio		65%	N/A	N/A
IMLR/influent ratio		3.0	3.0	3.0
MLSS, mg/L		3,000	120	100
HRTs	Swing Tank	20-min (Anoxic) <sup>†</sup>	23-min (Anoxic) <sup>†</sup>	42-min (Anoxic) <sup>†</sup>
	Aerobic #1, hrs	2.24	2.24	3.89
	Aerobic #2, hrs	2.24	2.24	3.89
Media Fill	Swing Tank	N/A	80%	80%
	Aerobic #1	46%	46%	46%
	Aerobic #2	46%	46%	46%

<sup>†</sup>Anoxic HRTs were calculated based on the total flow, including influent, RAS, and IMLR.

At the end of Phase 1 IFAS testing, batch tests were conducted with VF media from the aerobic tanks to examine the nitrification kinetics of the attached growth process. The VF media packing was removed, drained, and immersed into an identical aerated reactor with the same volume of clear water (~175 gallons) as the aerobic tanks. Ammonia was spiked to give an initial concentration of 50 mg/L. The residual ammonia concentrations were frequently analyzed over time to evaluate the nitrification rates attributed to the attached growth portion of the IFAS biomass. Liquid volume displacement and weight measurements for media with and without biomass were also conducted to estimate the biomass density.

## **Analytical Methods**

Composite samples from the influent and effluent of the pilot plant were routinely collected and analyzed for TSS, ammonia, TKN, nitrite, nitrate, TP, and CBOD<sub>5</sub> to determine the overall system performance. Grab samples from each stage of the pilot process (including influent and effluent) were also taken every other day for the concentrations of different nitrogen species (e.g. ammonia, nitrate, and nitrite) and soluble COD to establish performance profiles across the pilot reactors. Comparison between composite and grab samples confirmed the consistency of the influent and effluent data of the pilot.

Detailed pilot influent characterization, including the analysis of COD, filtered COD (soluble COD, SCOD), flocculated and filtered COD (*ff* COD), soluble CBOD<sub>5</sub>, volatile suspended solids (VSS) was regularly conducted for the purpose of calibrating and validating simulation design software. Other parameters, including suspended solids, D.O., and temperature in each aerobic stage were continually monitored and controlled with Hach SOLITAX and LDO probes to maintain proper operation using a computer and programmable logic controllers throughout the study.

Due to the high level of simultaneous nitrification and denitrification (SND) observed in the aerobic media reactors, only apparent nitrification rates based on ammonia removal efficiency instead of nitrate production were reported in this paper and it may include a typical 1-3% nutrient uptake associated with SCOD removal.

## **RESULTS AND DISCUSSION**

### **Air/Water Distribution on the Distribution Media**

The distribution media significantly improved the air and wastewater distribution through the VF media during the pilot study. A full distribution of air and wastewater over 36-inch media span was achieved with four (4) 1.2” tubular membrane diffusers (Figure 4 (a)). In a clear water experiment with the distribution media, the air and water distribution was able to reach an approximately 15.5 inches of width perpendicular to the direction of a single 3-inch tubular membrane fine bubble diffuser (Figure 4 (b)) in a single one-foot high media pack. This represents an average of 200% and 40% air and water distribution enhancements over no media and CF media systems, respectively (Figure 5). In full-scale installations with standard two-foot distribution media packs and 4-inch tubular membrane diffusers, air and water distribution can

expand a distance as far as 30 inches or greater, therefore supporting a typical 2-3 feet diffuser spacing layout. It was also observed that the air/water distribution was minimally, if at all, dependent on the air flow rate supplied to the diffuser with the distribution media (Figure 5). A maximized air/water distribution of 15.5 inches was achieved through the one-foot high distribution media pack even at a low air flow rate of 2.2 SCFM, as compared to 4.5 inches for no media system and 11 inches for the standard CF media system.

The capability of distribution media for enhanced air/water distribution is essential to fully utilize the entire media surface area for attached biomass growth and is also crucial to maintain effective biofilm control, especially in a fixed-in-place media system. The distribution media becomes even more important during periods of low air demand, such as off-peak hours when an aeration system is controlled by the process air requirements. It has been reported that some fabric media systems had difficulties in controlling undesirable heavy biomass growth due to non-optimized and insufficient air/water distribution and scouring through the entire media surface (Benisch et al., 2009).

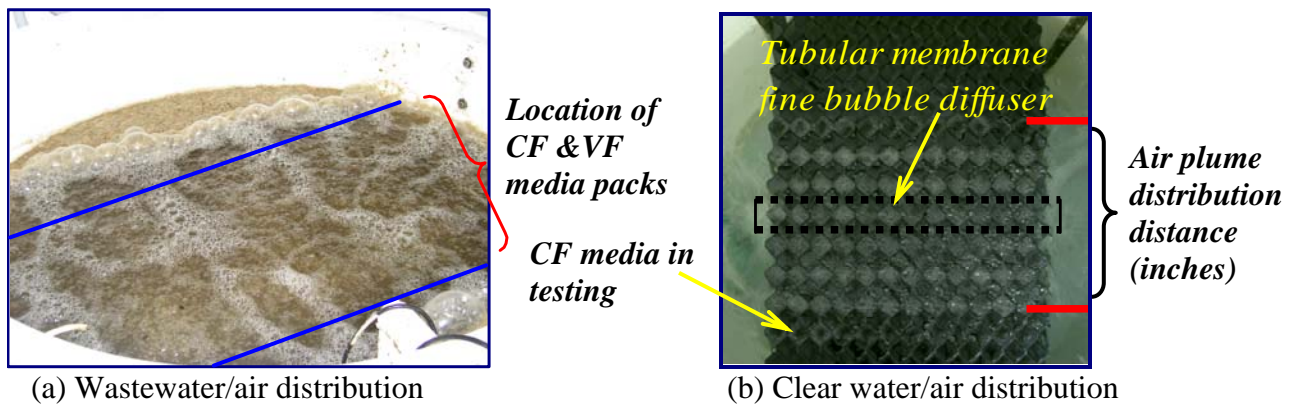


Figure 4 Aeration patterns over distribution media in wastewater and CF media in clear water

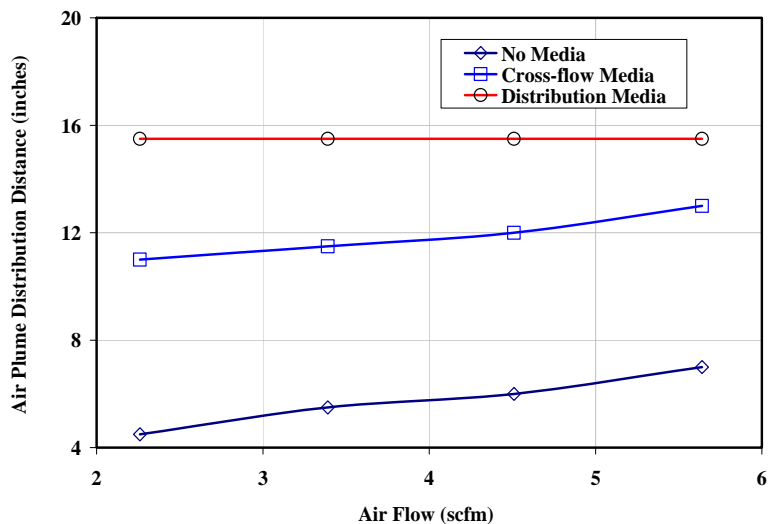


Figure 5 Air/water distribution distance of a single tubular fine bubble diffuser over no media, one-foot high CF, and one-foot high distribution media

## VF Structured Sheet Media IFAS Performance

The enhanced air and wastewater distribution provides a complete utilization of all media surfaces for attached biomass growth and also promotes intimate contact between biofilm and substrates (e.g.  $O_2$ , BOD, and  $NH_3-N$ ). Complete nitrification has been consistently observed for the IFAS testing period over about four (4) months (Figure 6). Nearly 100% ammonia removal was achieved in the VF media IFAS system for an ammonia loading up to approximately 15 lbs/kcf (Figure 7). The deviation of ammonia removal from 100% removal line at higher ammonia loadings could be attributed to the limited blower capacity (or D.O. limitation) in the pilot and also a higher organic load typically associated with an increased ammonia concentration (Randall and Sen, 1996).

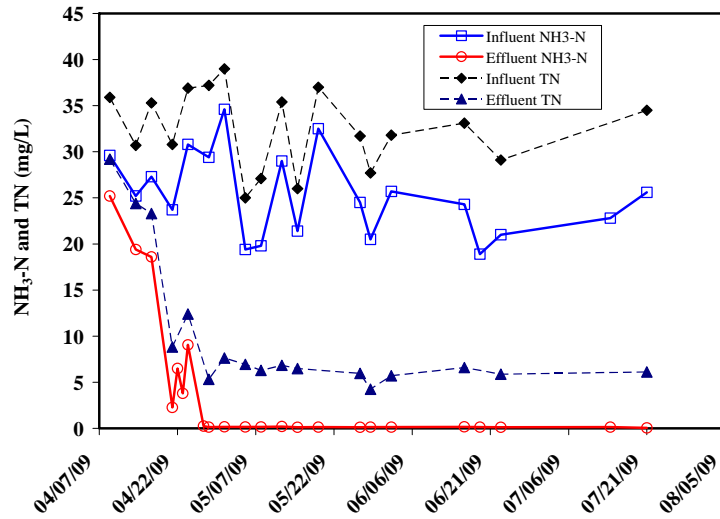


Figure 6 Ammonia and TN removal performance of the VF media in an IFAS operating mode

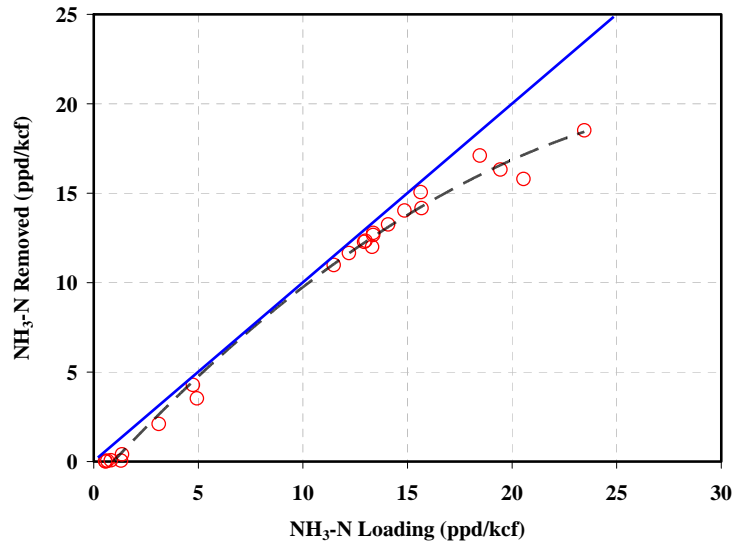


Figure 7 IFAS volumetric ammonia removal rates as a function of ammonia loads in the VF media system

The surface nitrification rate in the 1<sup>st</sup> aerobic tank was estimated to be about 0.65 g NH<sub>3</sub>-N/m<sup>2</sup>-day in a batch test, which was lower than the previously reported nitrification rate (e.g. 0.88 g/m<sup>2</sup>-day) associated with CF structured sheet media (Ye, et al., 2009). This was primarily due to the significantly higher SCOD removal rate occurring concurrently in the VF media system, 5.5 g SCOD/m<sup>2</sup>-day in this study versus 2.8 g SCOD/m<sup>2</sup>-day in the previous study. The results suggest that VF media may have comparable kinetic rates with CF media. This appeared to be consistent with the observation that the effective surface area, not the shape or size of the carrier was the most important design factor for a MBBR system (Ødegaard et al., 2000). Although the VF and distribution media feature enhanced mixing and scouring (Ye et al., 2010b), the CF media can be as efficient as the VF media for ammonia removal at low organic loads when the mixing and scouring is less crucial. However, due to its doubled specific surface area, the VF media can potentially offer twice the treatment capacity per unit media volume as the CF media.

As with a similar pilot study with free-floating media (Johnson, et al., 2004), comparable IFAS ammonia volumetric and surface-based removal rates were observed even with less media surface area density applied and under less favorable operating conditions (e.g. lower D.O., lower NH<sub>3</sub>-N loading, and higher SCOD loading)(Table 3). The enhanced nitrification associated with structured sheet media was attributed to its thin biofilm with dedicated aeration shearing and *constant* biofilm specific surface area for attached biomass growth (Ye, et al., 2009 and Sen, 2007).

Table 3 Comparison on volumetric and surface-based ammonia removal rates of CF, VF structured sheet, and free-floating media IFAS systems

<b>Parameters</b>	<b>Cross-Flow Structured Sheet Media<sup>1</sup></b>	<b>Vertical-Flow Structured Sheet Media</b>	<b>Free-Floating Plastic Media<sup>2</sup></b>
Aer #1 HRT, hrs	2.7	2.2	2.2
Aerobic SRTs, days	4-5	4-5	4-5
Average MLSS, mg/L	3,000	3,000	3,000
Average D.O., mg/L	3.15	3.32	4.50
Average NH <sub>3</sub> -N loading to Aer #1, ppd/kcf-tank	14.50	14.90	21.80
Media surface area density in Aer #1, ft <sup>2</sup> /ft <sup>3</sup> -tank	22	38	60
Concurrent BOD removal in Aer #1, g/m <sup>2</sup> -day	2.8	5.5	4.38
NH <sub>3</sub> -N removal rate in Aer #1, ppd/kcf-tank @ 20°C	14.0	13.52	13.21
Media surface NH <sub>3</sub> -N removal rate in the batch tests, g/m <sup>2</sup> -day @ 20°C	0.88 <sup>1</sup>	0.65	0.68

<sup>1</sup> Ye et al. (2009). Surface ammonia removal rate was estimated based on the performance difference between IFAS and activated sludge control.

<sup>2</sup> Johnson and McQuarrie (2002). The concurrent BOD removal rate in the 1<sup>st</sup> aerobic tank was estimated based on a conservative ratio of 4.0 g BOD removed per g NO<sub>3</sub>-N removed in the anoxic stage and a complete BOD removal in the 1<sup>st</sup> aerobic tank to the final effluent quality of 10 mg/L BOD.

Elevated simultaneous nitrification and denitrification (SND) activity was observed in the first aerobic media tank (Figure 8), which accounted for approximately 80% of the entire TN removal in the system based on nitrogen mass balance analysis. This has been previously attributed to the presence of oxygen gradients in the biofilm and suspended bacterial flocs in the mixed liquor (Barnard et al., 2004). A high level of SND was also reported in a pilot-scale MBBR process (Shaw et al., 2003). As opposed to a free-floating media system, the unique feature of the high internal recycle as created by the airlift pumping through a fixed structured sheet media tower may further contribute to the elevated SND observed in the VF media system.

Limited denitrification was achieved in the suspended anoxic stage due to the high residual D.O. (e.g. greater than 3.0 mg/L) as recycled from IMLR and RAS. An increased TN concentration was observed in the clarifier, possibly due to the high sludge blanket, causing digesting and releasing ammonia-nitrogen back to the process.

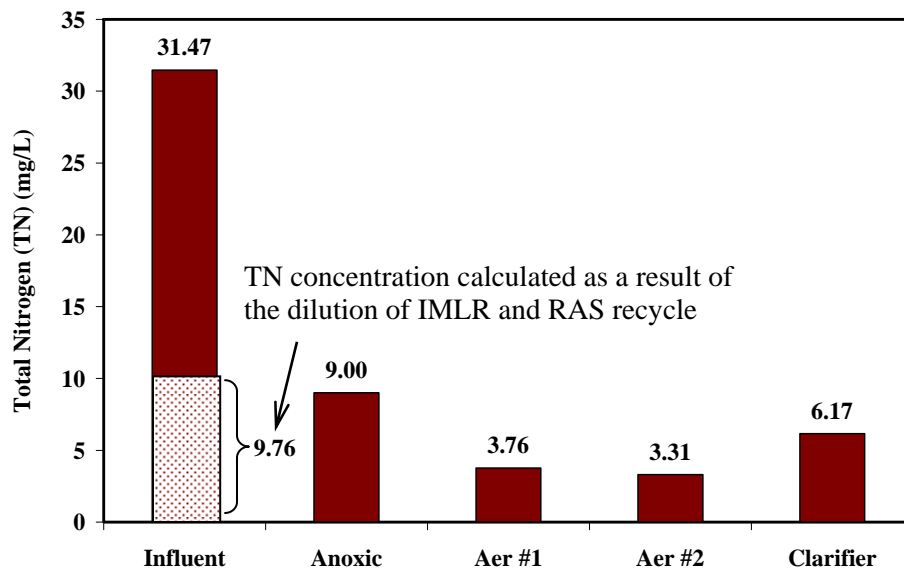


Figure 8 TN profile across the pilot system operating in an IFAS operating mode

### Soluble COD Removal in the VF Structured Sheet Media FBBR System

A biodegradable soluble COD (BSCOD) removal rate up to 30 g/m<sup>2</sup>-day was observed for a maximum SCOD load of 45 g/m<sup>2</sup>-day during the FBBR operation (Figure 9). The linear correlation between SCOD removal and loading rates indicated the organic degradation rate in the pilot was limited by the available BSCOD when an organic load less than 45 g/m<sup>2</sup>-day was applied. The deviation of the SCOD reduction line from the 100% removal line represents the presence of non-biodegradable SCOD in the wastewater and also a portion of SCOD that required longer HRTs (than those in the pilot) to be biodegraded. The maximum SCOD removal rate of 30 g/m<sup>2</sup>-day was also consistent with the reported value for a MBBR system (Odegaard et al., 2000), which could be due to the limitation of the blower capacity and D.O. concentrations in the pilot. With sufficient D.O. supply, it has been reported that a structured sheet media system was able to achieve a SCOD removal rate as high as 43 g/m<sup>2</sup>-day (Rodgers, 1999).

The slope of the SCOD reduction line indicated the efficiency of SCOD removal in the VF media system. The steeper the slope, the more efficient the system for SCOD removal. An approximately 65% SCOD removal was realized in the VF media system, which is about 15% greater than that observed in a MBBR system at an organic load of less than 60 g/m<sup>2</sup>-day (Ødegaard et al., 2004). The enhanced SCOD removal in the VF structured sheet media system could be due to the dedicated aeration shearing along with the media surface, promoting thin biofilm growth for better SCOD diffusion and oxygen transfer efficiency.

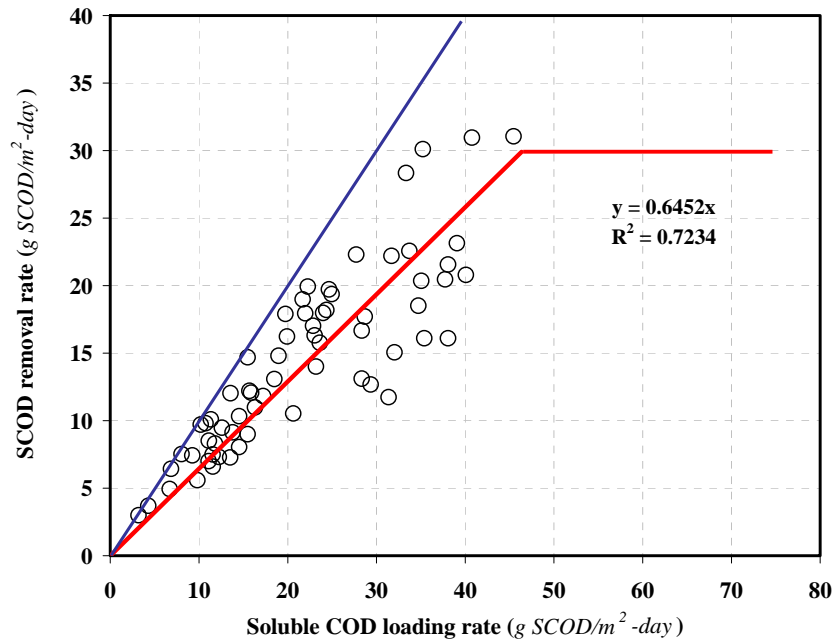


Figure 9 FBBR media surface SCOD removal rates versus surface SCOD loading rates

Figure 10 showed that the SCOD removal in the VF system increased as the bulk SCOD concentration increased up to 150 mg SCOD/L as studied in the pilot. Compared to a free-floating media system (Ødegaard et al., 2000), greater impact of bulk SCOD concentrations on the SCOD removal rates was observed, or greater SCOD removal rates were obtained at same bulk SCOD concentrations. For example, at bulk SCOD concentration of 100 mg/L, the SCOD removal rates were approximately 20 and 15 g/m<sup>2</sup>-day for FBBR and MBBR, respectively. This further supported the hypothesis that the vigorous dynamics in the VF system (as induced by the airlift pumping) promotes enhanced biofilm diffusion and kinetic rates. Figure 10 also identified that about 40 mg SCOD/L in the wastewater is non-biodegradable.

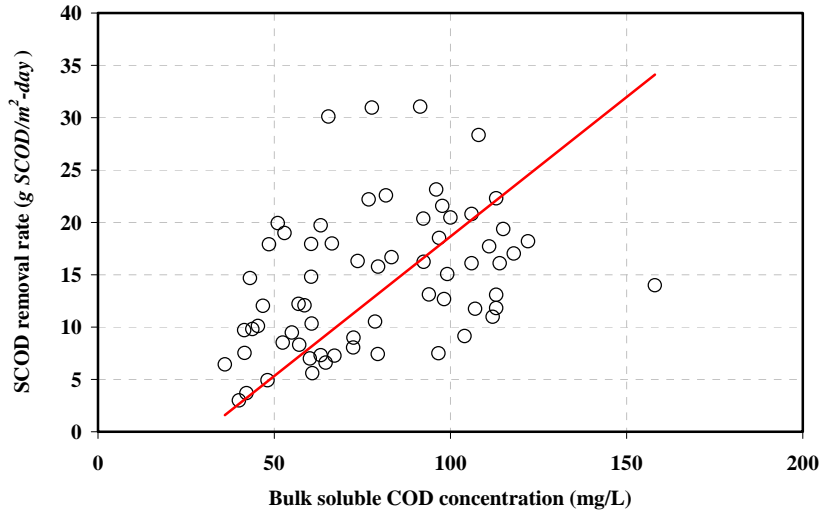


Figure 10 FBBR media surface SCOD removal rates versus bulk SCOD concentrations

### Ammonia and TN Removal in the VF Structured Sheet Media FBBR System

The study of applying VF structured sheet media for ammonia and TN removal in a FBBR process (or Phase 3 of the pilot) was conducted during a period of cold weather with influent temperatures ranging from 12-17°C. Despite the negative temperature effect, consistent full nitrification and significant TN removal were achieved over a period of about four (4) months (Figure 11). In comparison with Phase 1 IFAS testing, approximately half of the organic and ammonia loads were applied to the FBBR process due to its reduced influent flow rate (e.g. 1.3 gpm for IFAS and 0.75 gpm for FBBR). The comparable performance of ammonia removal in both IFAS and FBBR operations suggested that approximately 50% ammonia removal (or more when the temperature effect is taken into account) could occur on the media surface in a structured sheet media IFAS system when the MLSS concentration is about 3,000 mg/L.

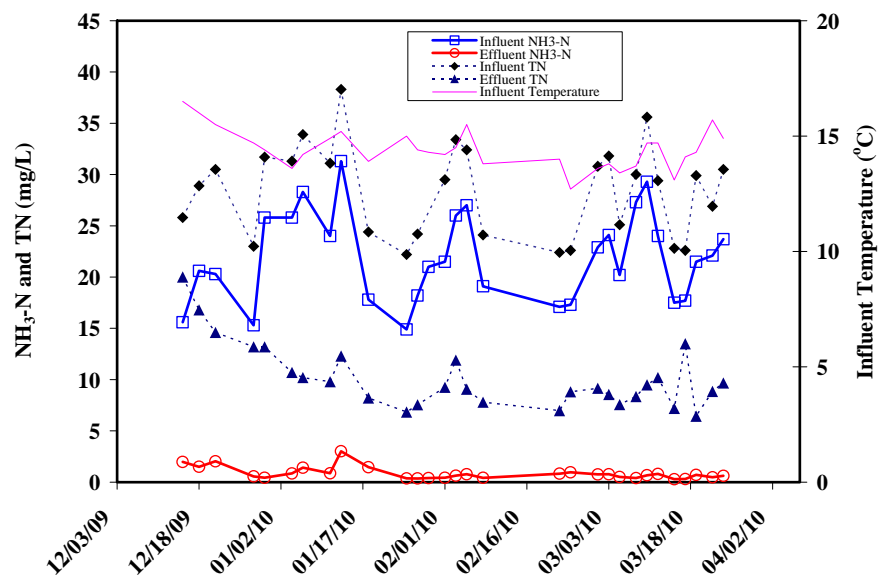


Figure 11 Ammonia and TN removal performance of the VF media in a FBBR operating mode

Figure 12 shows the observed ammonia removal rates in both aerobic #1 and #2 tanks as a function of concurrent SCOD removal rates. A tertiary surface ammonia removal rate up to 1.4 g/m<sup>2</sup>-day was obtained at a wastewater temperature of 15°C when the concurrent organic removal rates were less than 3.5 g SCOD/m<sup>2</sup>-day. It has been well recognized that nitrification tends to slow down as organic loads increase because heterotrophic bacteria outcompete nitrifiers (Ryhiner et al., 1994, Randall and Sen, 1996). It has also been reported that the nitrification rates in a MBBR reactor essentially became negligible at organic loads exceeding 5 g/m<sup>2</sup>-day (Hem et al., 1994). However, a minimum ammonia removal (e.g. less than 0.3 g NH<sub>3</sub>-N/m<sup>2</sup>-day) was observed even at SCOD removal rates greater than 5 g SCOD/m<sup>2</sup>-day in the pilot. The observed ammonia removal rates at high organic load appeared to be about 1-3% of the SCOD removal rate, consistent with the typical nutrient uptake ratio associated with BOD removal.

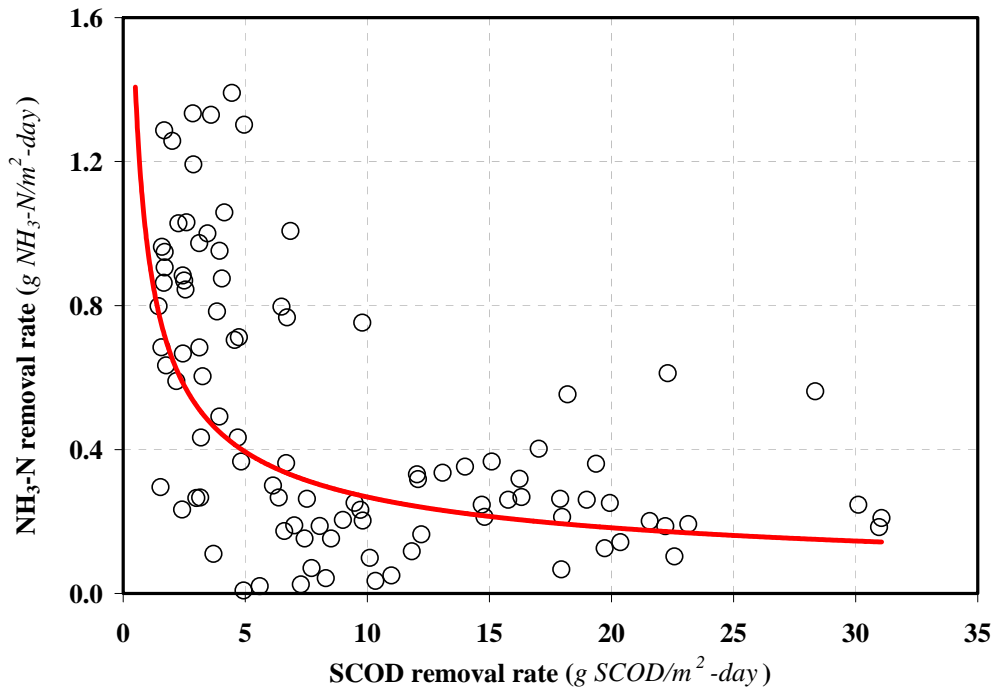


Figure 12 FBBR media surface ammonia removal rates versus surface SCOD removal rates at wastewater temperatures of 15-18°C

The correlation between ammonia removal rates and temperatures yielded a temperature correction coefficient of  $\theta=1.085$  for the VF structured sheet media FBBR system (Figure 13), which was close to the typical value (e.g.  $\theta=1.10$ ) used for a MBBR system (Boltz et al., 2009). The effect of residual DO concentrations on the ammonia removal rates is illustrated in Figure 14. The pilot system in the 3<sup>rd</sup> testing phase was operated at a relatively high residual DO concentration (e.g. average ~6.0 mg/L in the pilot as compared to typical 4.0-5.0 mg/L in full-scale applications) due to the reduced loads, the high-efficiency of the fine bubble diffusers, and also the limitations of the process control in the pilot. However, the observed strong dependency of nitrification rates on the residual DO concentrations was consistent with other media systems (Johnson et al., 2002), suggesting that advanced process control by regulating DO concentrations may be applied to compensate for the negative temperature impact during cold weather in a VF structured sheet media system. Furthermore,

in full scale operation with constant air supply, the low temperatures may have less influence on the process nitrification performance due to the positive effect of increased oxygen solubility and concentration (Ødeggard et al., 1994). Linear extrapolation of the regression line in Figure 14 intercepted the x-axis at a DO concentration of about 2.8 mg/L, indicating the minimum D.O. requirement for the nitrification process to occur in a VF structured sheet media system.

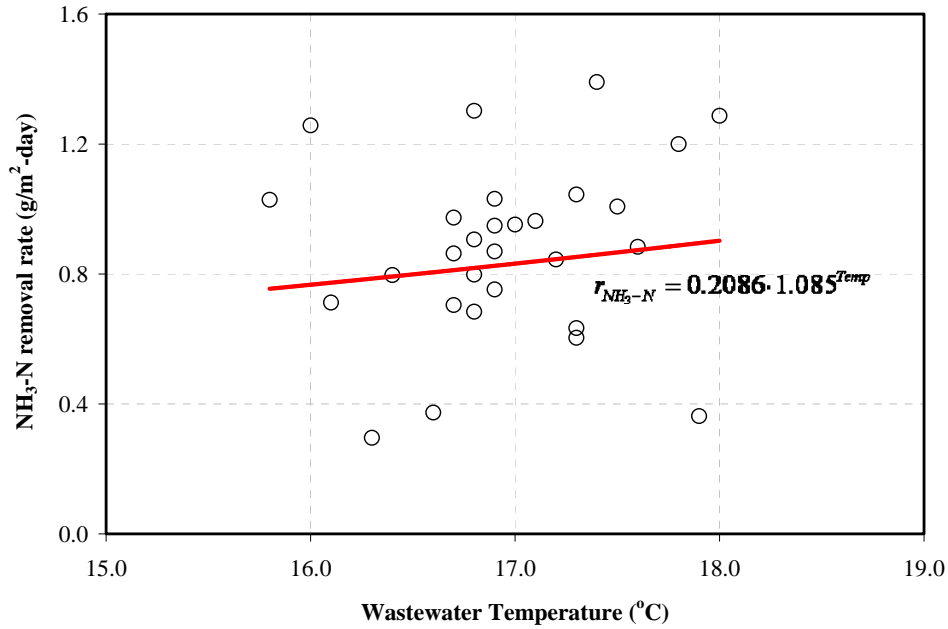


Figure 13 Effect of temperature on ammonia removal rates in the VF media FBBR system

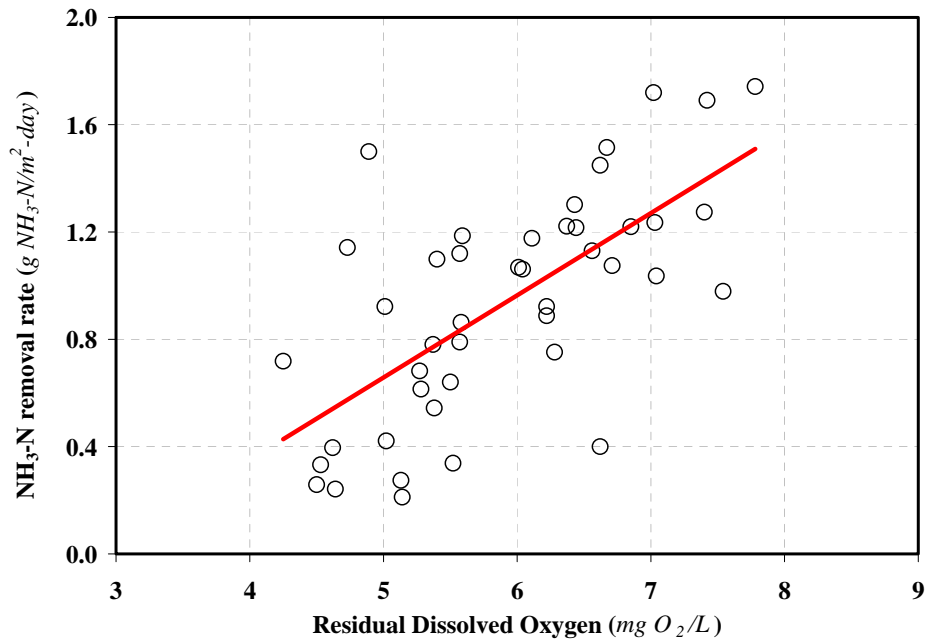


Figure 14 Impact of dissolved oxygen on the ammonia removal rates (normalized at 20°C,  $\theta=1.085$ ) in the VF media FBBR system

Elevated denitrification rates (e.g. 1.0-2.0 g NO<sub>3</sub>-N/m<sup>2</sup>-day) associated with the structured sheet media were observed even in a pre-anoxic process without external carbon sources, which appeared to be significantly higher than those observed in the MBBR systems (e.g. typically 0.3-1.1 g NO<sub>3</sub>-N/m<sup>2</sup>-day) (Boltz et al., 2009). This may be attributed to the presence of abundant soluble BOD in the pilot influent (e.g. up to 220 mg/L), high C/N ratio (e.g. greater than 8.0), and also enhanced diffusion over thin biofilm on the surface of structured sheet media due to the efficient mixing and scouring. High denitrification rates up to 3.8 g NO<sub>3</sub>-N/m<sup>2</sup>-day were also observed in a pre-denitrification unit with corrugated structured sheet media (Rodgers and Zhan, 2004). Similar to the IFAS process, elevated SND up to 70% of the entire TN removal was achieved in the first aerobic media tank of the FBBR process (Figure 16). The measurement of liquid velocity through the media indicated that the ratio of the flow induced by the airlift pumping through media to the influent flow was greater than 300 and far exceeded the typical internal recirculation ratio (e.g. 2-4) as used in a MLE process, promoting high level of SND in the VF media system.

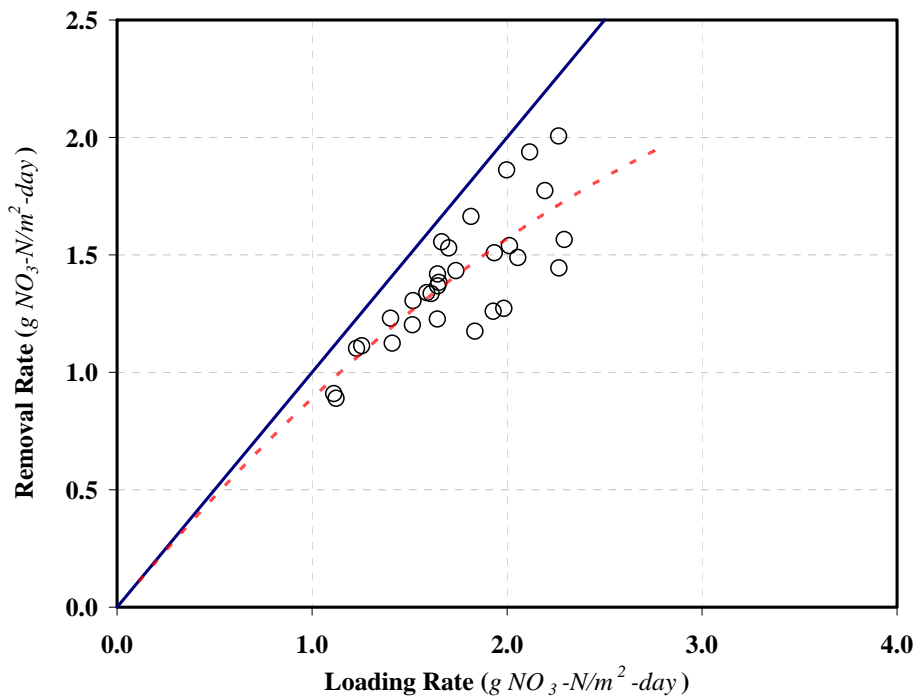


Figure 15 FBBR denitrification rates of structured sheet media in a pre-anoxic process at wastewater temperatures of 15-18°C

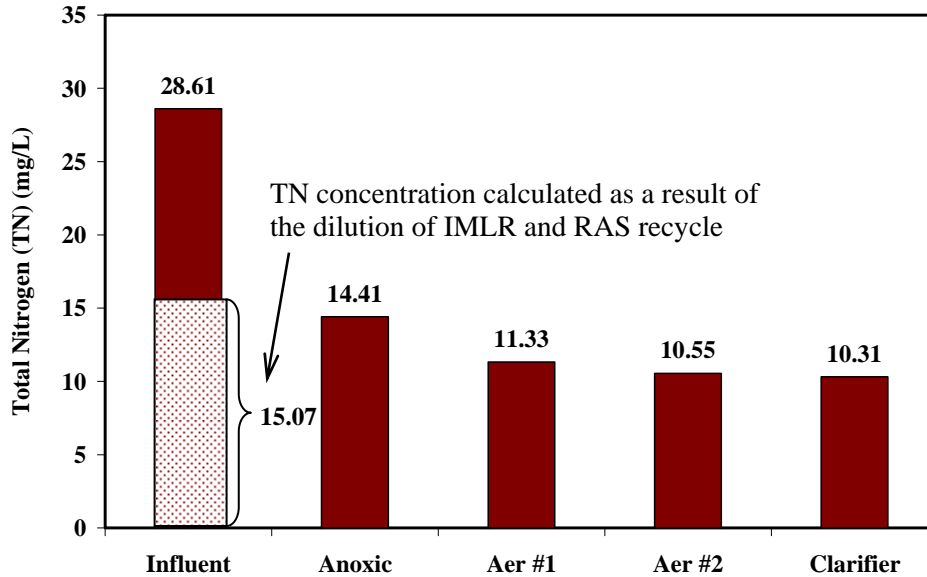


Figure 16 TN profile across the pilot system operating in a FBBR operating mode

### Comparison of VF Structured Sheet Media System with Other Media Systems

Favorable kinetic rates, such as nitrification, SCOD removal, and denitrification rates in the VF structured sheet media system have been consistently observed over other biofilm systems. This was mainly because the VF and distribution media system is able to provide dedicated and efficient scouring along the entire surface of the media, therefore maintaining “constant” effective biofilm specific surface areas and thin biofilms for enhanced substrate (e.g. SCOD, ammonia, and nitrate) and dissolved oxygen diffusion.

In comparison with free-floating media systems, the VF structured sheet media system provides more “constant” biofilm specific surface area and more dedicated scouring on the biofilm surface. As illustrated in the Figure 17, the contact between tumbling floating circular media and substrates or oxygen may not be as intimate and efficient as the structured sheet media system. The biomass thickness on the VF media has less impact on its biofilm specific surface area due to the open size (e.g. 19-mm for VF media versus typical 9-mm for circular carrier media) and thin biofilm (Sen et al., 2007, Ye et al., 2009). Although the reported bulk specific surface areas for various free-floating media are ranging 500-600  $\text{m}^2/\text{m}^3$  (Boltz et al., 2009), their biofilm specific surface areas are determined to be significantly less, ranging between 150-300  $\text{m}^2/\text{m}^3$  due to the limitation of the maximum media fill (Umble et al., 2009). In addition, free-floating media systems are typically characterized as completely mixed reactors, which may not be as efficient as the typical plug-flow configuration of a VF media system. Daigger and Parker (2000) reported that the uniform low ammonia concentration in a completely mixed reactor may limit the nitrifier growth. In contrast, the ammonia gradient in a plug-flow reactor can promote nitrifier growth at their maximum rates. Parker and Wanner (2007) also reported that the overall nitrification rate observed in a plug flow configuration was more than 50% higher than that obtained in a completely mixed reactor.

As opposed to fixed-in-place fabric media systems, the VF media system promotes full utilization of the entire media surface by applying the unique distribution media. Without an efficient distribution method, it will be difficult for the fabric media systems to deliver diffused air to the entire media surface due to the non-continuously located diffusers. Fabric media systems also possess the challenge with limited horizontal scouring, resulting in heavy biomass growth, reducing effective media surface area, and inducing red worm growth (Benisch et al., 2009, Jackson et al., 2007, Hubbell et al., 2006, Sen et al., 1993 and 2000).

Other features of the VF media system include its compatibility with fine bubble diffusers for process and mixing aeration requirements (versus coarse bubble diffusers as typically used in free-floating and fabric media systems) and also its elevated SND activity due to the high internal re-circulation through media as created by the airlift pumping.

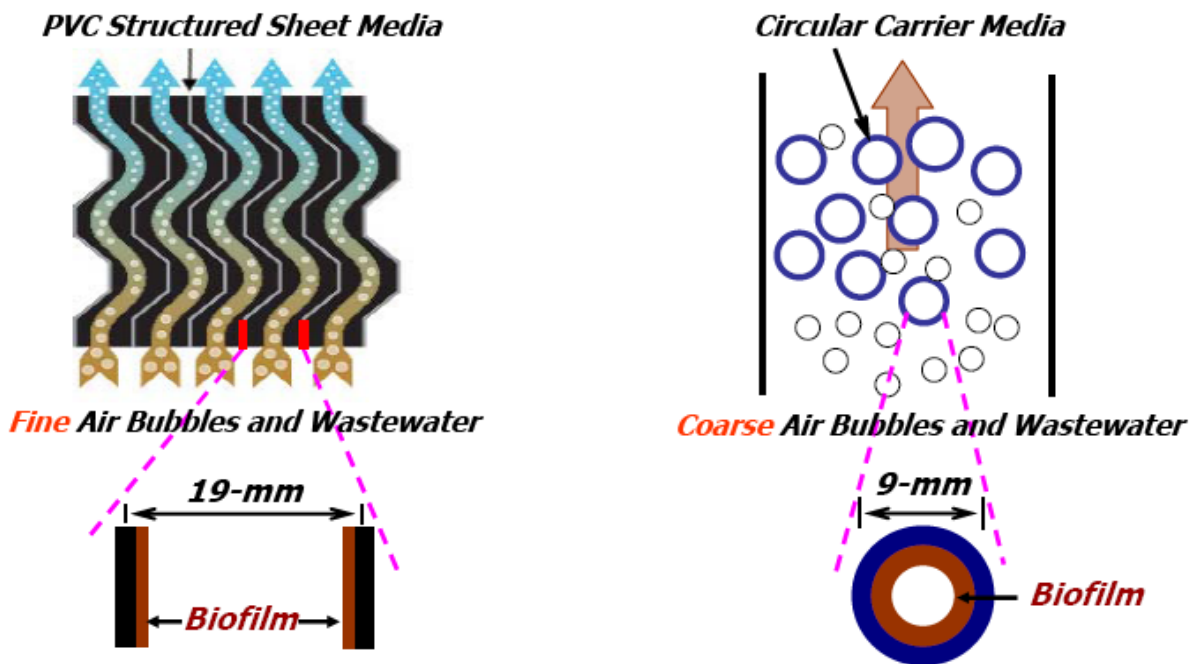


Figure 17 Schematics of structured sheet and circular carrier media with biomass

### Settleability of Solids from Structured Sheet Media IFAS and FBBR Systems

Figure 18 & 19 shows the effluent TSS observed in the IFAS and FBBR operations of the pilot. The average Sludge Volume Index (SVI) of the IFAS mixed liquor was measured to be approximately 140. Although the observed SVI in the pilot is typical for a conventional activated sludge process, it may not be representative for a full-scale wastewater treatment plant due to the deteriorated solids settling characteristics in the pilot clarifier as a result of sludge accumulation. A SVI as low as 80 was detected in a full-scale structured sheet media IFAS system (Ye et al., 2010a). Figure 19 demonstrated that the FBBR process was able to achieve a consistent effluent quality with less than 30 mg/L TSS.

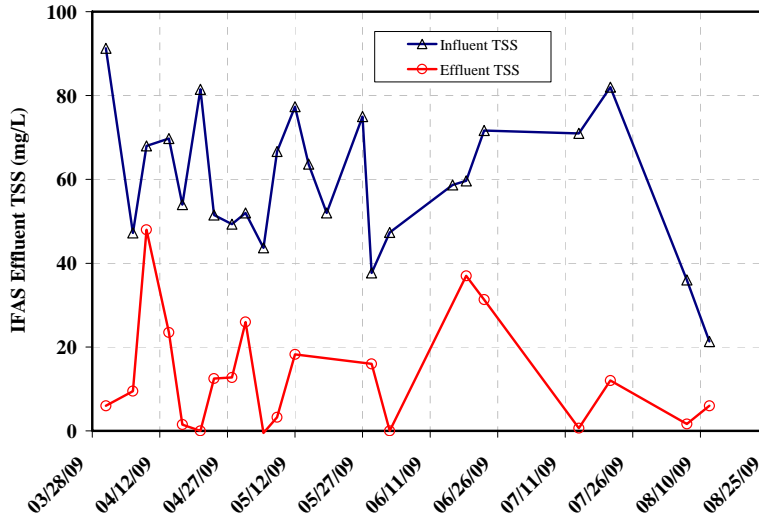


Figure 18 TSS in the clarified effluent following the IFAS VF media system

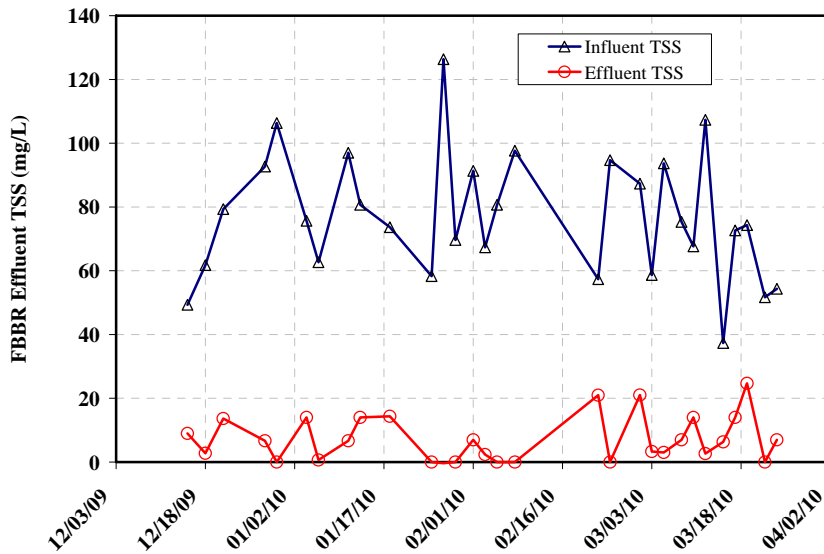


Figure 19 TSS in the clarified effluent following the FBBR VF media system

## CONCLUSIONS

This study has demonstrated that the high surface area density VF media system is capable of achieving complete nitrification and high-rate BOD removal for both IFAS and FBBR applications. As one of the key elements in the VF media system, the distribution media not only maximized the air/wastewater distribution over the entire surface area of the media, but also optimized the airlift pumping through media for adequate mixing and effective biomass control. Approximately 200% and 40% air/water distribution enhancements were achieved over no media and standard CF media systems, respectively with the distribution media. The distribution characteristic of minimum dependency on the air flow rate in the distribution media system also provide flexible process air control for the period of low air demand (e.g. off-peak hours).

Favorable kinetic rates have been consistently observed in the VF structured sheet media system, mainly due to intimate contact between thin biofilm and substrates/oxygen as promoted by the dedicated aeration. A media surface ammonia removal rate of 0.65 g/m<sup>2</sup>-day was obtained at a concurrent SCOD removal rate of 5.5 g/m<sup>2</sup>-day in the VF media IFAS process. A tertiary ammonia removal rate up to 1.4 g/m<sup>2</sup>-day was observed at an organic load of less than 3.5 g/m<sup>2</sup>-day in the FBBR system and a wastewater temperature of 15°C. The maximum SCOD removal rate on the VF media was estimated to be approximately 30 g/m<sup>2</sup>-day at a SCOD load of 45 g/m<sup>2</sup>-day during the FBBR operation. Elevated denitrification rates of 1.0-2.0 g NO<sub>3</sub>-N/m<sup>2</sup>-day were also achieved in a pre-anoxic process with structured sheet media. The study also showed that a significant amount of SND occurred in the aerobic VF media reactors even with a high residual DO concentration up to 6.0 mg/L. It has been hypothesized that the high internal wastewater recirculation through media as created by the airlift pumping may contribute to the elevated SND.

Other findings from the pilot study may also have important implications for full-scale designs. First, as opposed to the VF media with an enhanced flow/air distribution and twice the treatment capacity per unit media volume, CF media may be only applicable at low organic loads when mixing and scouring is less crucial. Second, fine bubble diffusers are compatible with the VF media to meet the process and mixing aeration requirements. Tapered aeration with fine bubble diffusers may be desirable for the typical plug-flow VF media system to optimize kinetic rates and reduce energy consumption. Third, in addition to its capability for full nitrification and high-rate SCOD removal, the VF media FBBR process with a properly designed clarifier can also reliably achieve a quality effluent with a TSS of 30 mg/L or less.

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