Pilot Testing of Structured Sheet Media IFAS for Wastewater Biological Nutrient Removal (BNR)

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ABSTRACT

IFAS systems with various media have been increasingly implemented for enhanced nutrient removal. PVC structured sheet media have received little attention for IFAS applications despite their wide use for attached biomass retention in trickling filters. This pilot study was first conducted to evaluate the fabric media IFAS proposed for Springettsbury Township, Pennsylvania WWTP. Observations from the fabric media testing led to the following investigation of PVC structured sheet media IFAS to meet stringent nutrient limits.

The pilot results demonstrated that structured sheet media IFAS is capable of achieving complete nitrification with a surface nitrification rate of 0.88 g/m^2-day. No media fouling was encountered. The unique shearing pattern from airlift pumping through structured sheet media creates thin and high-density biofilm for efficient oxygen and substrate mass transfer. The detrimental effects of red worm growth observed in this study with fabric media were not similarly observed with PVC structured sheet media.

KEYWORDS: Integrated Fixed-Film Activated Sludge (IFAS), PVC Structured Sheet Media, Nitrification, Biological Nutrient Removal (BNR), Fabric Media.

INTRODUCTION

IFAS Technology

The Integrated Fixed-film Activated Sludge (IFAS) process incorporates fixed-film media in a suspended growth reactor to increase the overall biomass inventory for an enhanced treatment without increasing solids loading to the subsequent clarifiers. The IFAS technology has been increasingly recognized as an economical alternative for biological nutrient removal (BNR) upgrades and treatment capacity expansion in conventional activated sludge plants. A number of full-scale IFAS facilities have been installed in the United States over the past decade (Randall and Sen, 1996, Johnson and McQuarrie, 2002, Jackson *et al.*, 2007). Various types of media have been used for IFAS installations, including free-floating media (e.g. Kaldness and IDI ActiveCell plastic media, and Captor and Linpor sponge media) and fixed-in-place media (e.g. fabric media such as AccuWeb and Ringlace, and fixed-in-place plastic media such as AccuFAS and Bio-2-Sludge).

In comparison to other IFAS media, fixed-in-place plastic media such as polyvinyl chloride (PVC) structured sheet packings have received less attention for potential IFAS applications in the United States although they have been long proven as support materials for attached biomass growth in trickling filter installations. The operation of six full-scale IFAS systems in Europe has demonstrated the process capability for complete nitrification with fixed-in-place plastic media (Muller, 1998, Sen *et al.*, 2000). It has also been reported that a properly designed aeration system would provide sufficient mixing and improve the mass transfer of substrates and oxygen in a fixed-in-place media system (Rusten 1984, Odegaard and Rusten, 1990, Ryhiner *et al.*, 1992).

Background of the Springettsbury Township, Pennsylvania WWTP

As a result of the current Chesapeake Bay Tributary Strategy (CBTS) for nutrient and sediment reductions in the Chesapeake Bay Watershed, the Pennsylvania Department of Environmental Protection (DEP) has recently enacted new total nitrogen (TN) and total phosphorus (TP) discharge limits for sewage facilities with a design flow greater than 0.4 MGD. Concentrations of 6.0 mg/l for TN and 0.8 mg/l for TP have been adopted as the discharge limits in order to achieve the overall cap load objectives of the CBTS.

The existing Springettsbury Township, Pennsylvania Wastewater Treatment Plant (STWWTP) is comprised of headworks with screening and a grit chamber, primary sedimentation tanks (not in use), anoxic/aerobic (A/O) basins (MLE process), and chlorination and dechlorination units, with final effluent discharging to Codorus Creek, a tributary of the Susquehanna River to the Chesapeake Bay. Although the existing plant features nitrogen removal by the MLE process and phosphorus removal by chemical precipitation in the secondary clarifiers, the more stringent nutrient limits of TN and TP required the plant to be upgraded for enhanced nutrient control.

Due to economic concerns and site constraints, an anaerobic/anoxic/oxic (A^2/O) process using IFAS technology was determined to be the most feasible BNR alternative for the plant. The proposed process involved converting the existing primary clarifiers into anaerobic zones for biological phosphorus removal and partitioning the existing A/O basins into multi-staged anoxic and aerobic zones for enhanced biological nutrient removal. An IFAS media was proposed for the aerobic stages to compensate for the reduced aerobic retention time in the new configuration to achieve the required nitrification.

Objectives of the Pilot Study

The pilot study was initially conducted to confirm the performance of a fabric media in conjunction with the A^2/O process design for the required TN and TP removal. The observations from the performance of the fabric media later led to follow-up studies on PVC structured sheet media for potential IFAS applications. The objectives of the pilot study were therefore expanded to evaluate the capability of the PVC structured sheet media IFAS to meet stringent nutrient limits, to investigate impacts of temperature, soluble chemical oxygen demand (COD), and residual dissolved oxygen (D.O.) on the nitrification process, and to determine nitrification rates for a PVC structured sheet media IFAS system.

METHODOLOGY

Process Description of the Pilot Facility

The pilot plant consisted of two staged anaerobic tanks, one anoxic tank, and two staged aeration tanks with 45.8% (by vol.) media fill in each (Figure 1). The tank volumes, design flow, and loading rates of the pilot study were scaled down from the proposed full-scale A^2/O design. Given that the existing primary clarifiers were bypassed and not in use, the influent to the pilot system was supplied by a submersible pump placed in the effluent channel of the existing grit chamber. A chiller and a heat exchanger were used to control the temperature of the influent to the pilot system. The treated wastewater exited over the effluent weir of the clarifier and was directed to the plant headworks. Sludge was also periodically wasted and returned back to the headworks. Figure 2 shows the simplified flow schematic of the pilot process.

Figure 1 Interior photograph of the pilot trailer

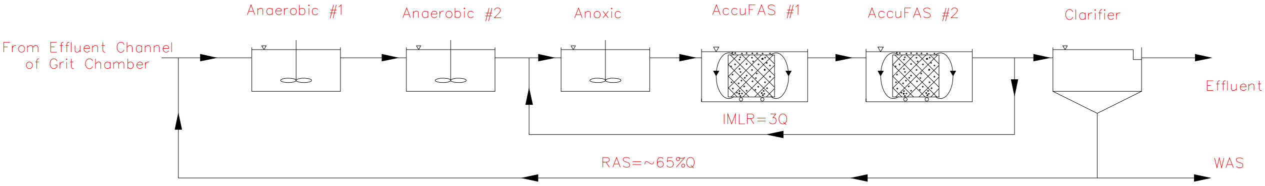
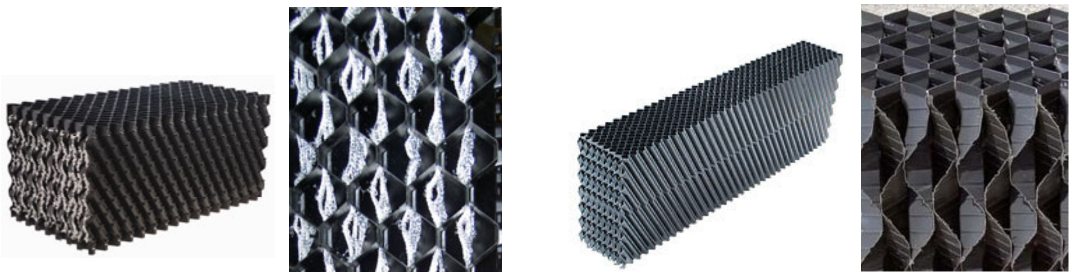


Figure 2 Flow schematic of the pilot process at Springettsbury Township, Pennsylvania

Description of Pilot Testing Phases

The pilot study was conducted at the Springettsbury Township, Pennsylvania wastewater treatment plant over an eight-month period from August 2007 to March 2008. Two types of media were tested in aeration basins: 1) a fabric media, and 2) a PVC structured sheet media (Figure 3). The fabric media contains polyester fabric web material supported by PVC structured sheet. The PVC structured sheet media is created by joining adjacent sheets of corrugated PVC sheets with solvent bonding and forming them into modules, which provide a continuous and horizontal redistribution of air and mixed liquor.



AccuWeb SST Fabric Media AccuFAS PVC Structured Sheet Media

Figure 3 Fabric media and PVC structured sheet media

The pilot study was ultimately segmented into three testing phases, consisting of (1) fabric media testing, (2) PVC structured sheet media testing, and (3) an activated sludge control experiment. Phase (1) and (2) testing were carried out for approximately a 14-week period each. The pilot system was also operated as an activated sludge system without media during the last stage of the testing for about one month. The design operating conditions of the pilot facility through the three testing phases are summarized in Table 1.

Table 1 Design operating conditions of the pilot facility

Parameters	**Pilot Operating Conditions**
Influent source to the pilot plant	Effluent of plant primary clarifiers
Flow rate, lpm (gpm)	4.09 (1.08)
RAS/influent ratio	65%-100%
IMLR/influent ratio	3.0
Overall HRT, hrs	9.0
MLSS, mg/L	~3,100
[†]Media fill fraction – Aerobic Tank #1	45.8%
[†]Media fill fraction – Aerobic Tank #2	45.8%

[†]*Phase (1) and (2) only*

At the end of PVC structured sheet media testing, batch tests were also conducted with this media from the 2nd aerobic tank to examine the nitrification kinetics of the attached growth process. The PVC structured sheet media packing was pulled out, drained, and immersed into an identical aerated reactor with the same volume of clear water (~175 gallons) as the 2nd aerobic tank. 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 biofilm thickness, biomass density, and dry biomass weight.

Analytical Methods

Composite samples from the influent and effluent of the pilot plant were routinely collected and analyzed in-house and also continuously verified with external certified laboratory testing for total suspended solids, ammonia, total Kjeldahl nitrogen (TKN), nitrite, nitrate, total phosphorus, and carbonaceous biological oxygen demand ($CBOD_5$) to determine the overall system performance. Detailed pilot influent characterization, including the analysis of total chemical oxygen demand (COD), filtered COD (soluble COD), flocculated and filtered COD (*ff* COD), soluble $CBOD_5$, volatile suspended solids (VSS) was also regularly conducted for the purpose of simulation modeling calibration.

Grab samples from each stage of the pilot process (including influent and effluent) were taken daily and measured in-house for the concentrations of different nitrogen species (e.g. ammonia, nitrate, and nitrite) and soluble COD to establish performance profiles across the pilot reactors. The employed sampling and analytical procedures for this study were consistent with those identified in Standard Methods (Greenberg *et al.*, 1985). Comparison between grab and composite samples confirmed the consistency of the influent and effluent data of the pilot. Diurnal samples of the pilot influent were also collected and analyzed for suspended solids, ammonia, and soluble COD to evaluate the diurnal variations of organic, ammonia, and solids loading to the pilot process.

In addition to the above parameters, mixed liquor suspended solids (MLSS), D.O., and temperature in each aerobic stage were continually monitored with Hach SOLITAX and LDO probes and SC100 controllers to maintain proper operation using a computer and programmable logic controllers throughout the study.

RESULTS AND DISCUSSION

Pilot Influent Characteristics and Operating Conditions

Figure 4 shows the pilot influent characteristics. The Springettsbury Township, Pennsylvania facility primarily treats domestic wastewater with influent ammonia, BOD and TSS concentrations averaging approximately 20, 200, and 300 mg/L, respectively, after screening and grit removal. Spikes of ammonia as high as 35 mg/L were detected due to periodic septage deliveries to the treatment plant. It was also observed that ammonia concentrations in the pilot influent varied by more than 100% over the course of a day, from 12 mg/L at 6-9 am to 24 mg/L at 12-1 pm (Figure 5).

Figure 6 shows the operating conditions of the pilot plant. An average MLSS concentration of 3,100 mg/L was maintained throughout the study at a sludge wasting rate of 130 L/d. This gives a suspended aerobic SRT of approximately 4-5 days. The aerobic tanks were operating at residual D.O. concentrations of 3-4 mg/L for sufficient aeration and mixing. The wastewater temperatures were averaging $20^{o}C$ during the fabric media testing from August to November. The PVC structured sheet media testing was conducted throughout the cold weather season from December to February, with wastewater temperatures ranging from 12 to 18 ^{o}C. The chiller was used to create temperature fluctuations for a short time during structured sheet media testing in order to observe the responses of the nitrifiers on the structured sheet to the temperature shocks.

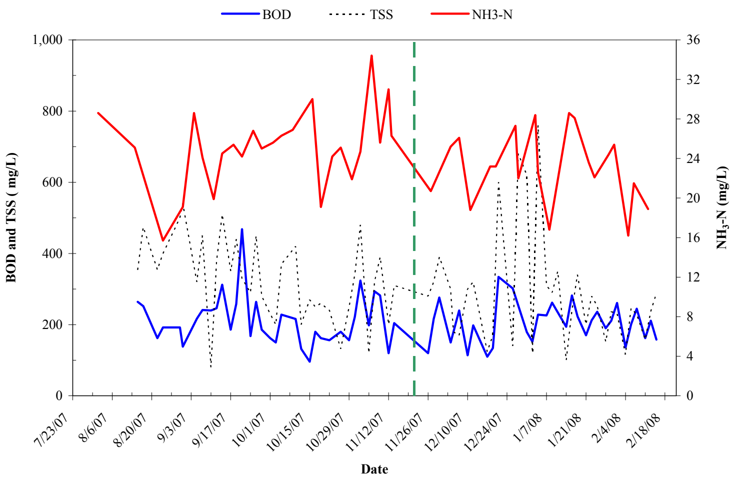


Figure 4 Effluent from grit chamber in the Springettsbury, Pennsylvania WWTP

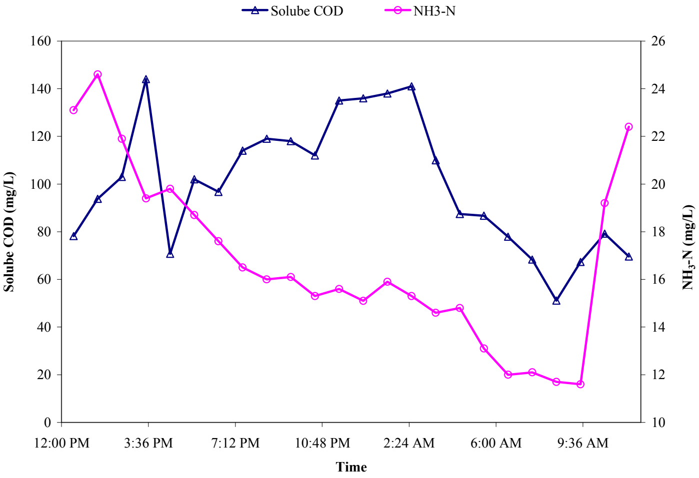


Figure 5 Diurnal soluble COD and NH_3-N concentrations in the effluent from grit chamber

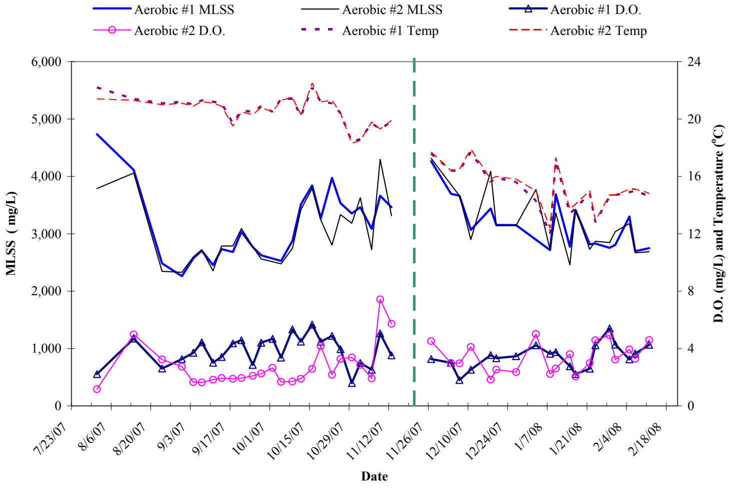


Figure 6 Operating conditions in the pilot facility

Nitrification on the Fabric Media

The first three-month operation of the pilot facility with the fabric media was problematic with inconsistent nitrification. Although complete nitrification was initially achieved with nitrifier seeding and desirable wastewater temperatures, the process performance degraded dramatically after the first month (Figure 7), which was later found to be the result of excessive red worm growth. It was also observed that red worms tended to grow on the fabric media, but not on the structured sheet support as can be seen by the color difference between the fabric media and the structured sheet (Figure 8). The presence of red worms significantly reduced the nitrification capacity of the system and caused ammonia breakthrough in the pilot effluent.

A number of references have reported red worm bloom on the fabric media, including rope-type media (Lessel, 1991, Sen *et al.*, 1993) and web-type media (Hubbell *et al.*, 2006, Jackson *et al.*, 2007). It has been suggested that the physical conditions (e.g. media shape or pore sizes) of the fabric media may contribute to the red worm growth (Sen *et al.*, 2000). Different methods have been reported to remediate the excessive red worm populations, including "Air On/Off" operation followed by a chlorination procedure (Sen *et al.*, 1993, Copithorn *et al.*, 2006) and use of a redundant aeration grid underneath the fabric media (Hubbell *et al.*, 2006).

Although remedial actions such as complete nitrifier re-seeding and vigorous aeration were attempted to control red worms, no consistent nitrification was observed in the first three months of this study. However, the observation of excessive red worm growth on the fabric media versus no comparable presence of red worms on the structured sheet subsequently led to the investigation of using structured sheet media for IFAS applications.

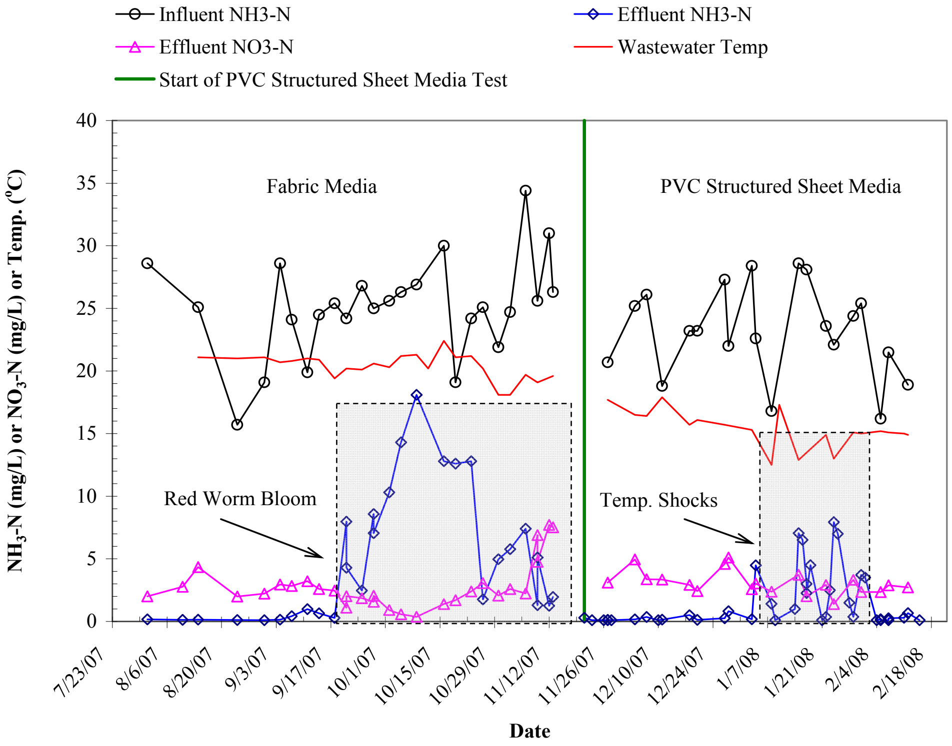


Figure 7 Nitrification performance of the fabric media and PVC structured sheet media IFAS systems

Figure 8 Excessive red worm growth on the fabric media

Nitrification on the PVC Structured Sheet Media

The replacement of fabric media with structured sheet media in the aeration tanks significantly improved the overall nitrification performance of the system (Figure 7). Enhanced ammonia removal was consistently achieved even with a gradual temperature drop as compared to the poor nitrification during the testing period of fabric media. A thin layer of biofilm with relatively uniform distribution over the surface of the media was developed over time and no red worms were observed (Figure 9). Although a nitrification upset was detected as a result of artificial shocks of wastewater temperature, the pilot plant recovered quickly as the temperature stabilized.

Figure 9 PVC structured sheet media with healthy biomass

Figure 10 shows the temperature normalized ammonia removal rates as a function of ammonia loadings obtained in the PVC structured sheet media IFAS system. It can be seen that ammonia removal rates increased as the ammonia loadings increased, up to an ammonia loading of about 12 lbs/kcf and leveled off afterwards. Nearly 100% ammonia removal was achieved in the structured sheet media IFAS system with an ammonia loading less than 12 lbs/kcf. This was consistent with the observed maximum ammonia loading (~10 lbs/kcf) for compete nitrification in a free-floating media IFAS system (McQuarrie *et al.*, 2004). The flat ammonia removal rates at higher ammonia loadings could be due to possible D.O. limitation (Hem *et al.*, 1994) and higher soluble COD loadings associated with ammonia loading increases (Randall and Sen, 1996).

By comparing the ammonia removal efficiencies between the structured sheet media IFAS and activated sludge systems, the media surface nitrification rate was estimated to be approximately 0.88 g NH_3-N/m^2/day at an average NH_3-N loading of 14.5 ppd/kcf in the 1st aerobic stage. This surface nitrification rate was approximately one third of the total ammonia removal rate of the structured sheet media IFAS system, indicating the suspended mixed liquor was operating well beyond critical SRT; the system was not ammonia loading stressed; and the majority of the ammonia removal occurred in the suspended mix liquor.

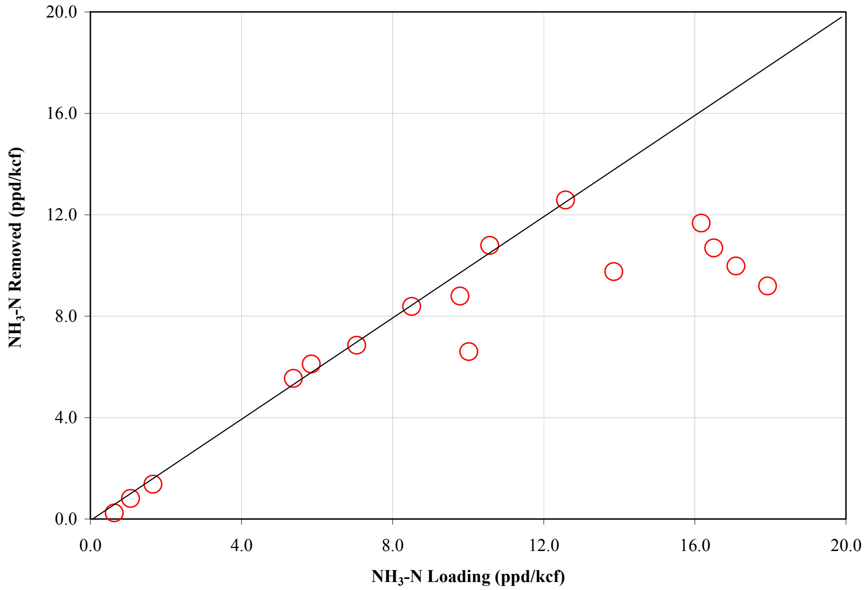


Figure 10 Nitrification in the structured sheet media IFAS system (T=20°C, k_T=1.035)

Table 2 summarizes the nitrification rates of PVC structured sheet and free-floating plastic media IFAS systems. Although it has been reported that the free-floating plastic media has typical surface nitrification rates of 0.4-1.0 g NH_3-N/m^2/day (Sen *et al.*, 2000), the study of Johnson and McQuarrie (2002) was chosen for comparison because of its similarity to our pilot study. Both studies were pilot scale with similar process configurations and operating conditions. The results show that when compared to the free-floating media IFAS, the structured sheet media IFAS had a comparable overall ammonia removal rate of 0.4 g NH_3-N/m^3-media/day, even with a lower average operating D.O. and less ammonia loading, which would typically have negative impacts on the nitrification rates (McQuarrie *et al.*, 2004, Johnson *et al.*, 2004). Additionally, almost three times less surface area of structured sheet media was used in the IFAS system to achieve the similar nitrification rate, suggesting other factors than the *apparent* media surface area must play an important role on the efficiency of ammonia removal in an IFAS system.

The observed more effective surface nitrification on the PVC structured sheet media could be attributed to two factors. First, the dedicated physical aeration/water shearing along the structured sheet surface tends to create a thin biofilm/boundary layer for enhanced oxygen transfer efficiency and improved substrate mass transfer (Figure 11). Second, unlike structured sheet media, biofilm growth on the interior surface of a closed circular carrier media would likely reduce its effective surface area due to the decreased inner circumference (Figure 12). The smaller the circular media, the more significant the reduction of “effective surface area” as a result of biofilm growth on the media. Also, abrasion from the normal tumbling action of the floating circular media in the reactor can remove the slimes from the media surface, further reducing the effective surface area. In the contrast, the structured sheet media has relatively open spacing and bacteria tends to grow thin biofilm outward from the media surface, thus keeping the effective surface area constant.

Table 2 Comparison on nitrification rates of PVC structured sheet and free-floating plastic media IFAS systems

Parameters	**PVC Structured Sheet Media**	**Free-Floating Plastic Media**[1]
Aerobic process in pilot	Two-stage	Two-stage
Tank volume, liter (gallon)	662 (175)	662 (175)
Water temperature, °C	15	14
Average dissolved oxygen, mg/L	~3.15	~4.5
Media fill percentage	45.8%	40%
Media specific surface area, m^2/m^3 (ft^2/ft^3)	157 (48)	500 (152)
Total media surface area, m^2 (ft^2)	**48 (512)**	**132 (1,420)**
Average NH_3-N loading to 1st stage, kg/m^3-d (ppd/kcf-tank)	0.233 (14.50)	0.350 (21.80)
Observed IFAS NH_3-N removal rate in 1st stage, kg/m^3-d (ppd/kcf-tank)	0.192 (12.0)	0.172 (10.75)
Overall IFAS NH_3-N removal rate in 1st stage, kg/m^3-d (ppd/kcf-media)	**0.420 (26.20)**	**0.430 (26.88)**

[1] *Johnson and McQuarrie (2002)*

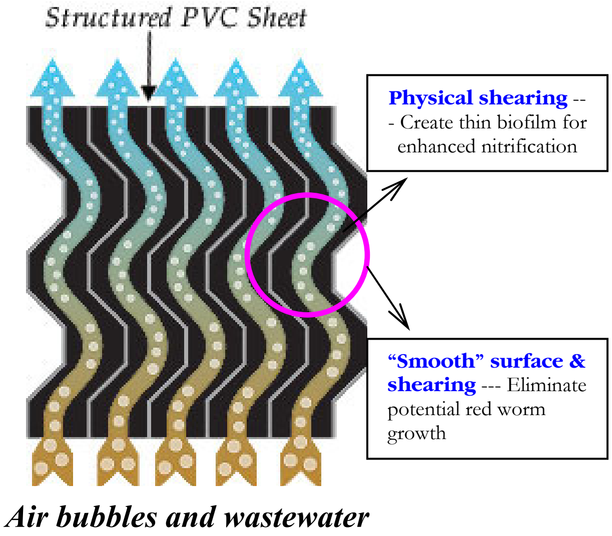


Figure 11 Schematic of submerged and aerated structured sheet IFAS media

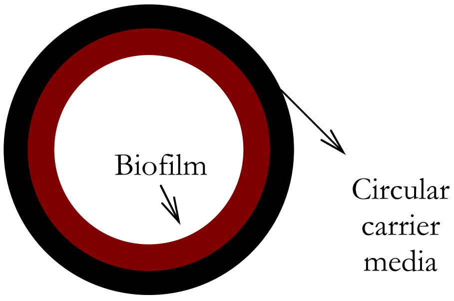


Figure 12 Schematic of a hypothetical circular carrier media with biomass

The batch nitrification test on the structured sheet media from the 2nd aerobic stage yielded a surface ammonia removal rate of 0.4 g NH_3-N/m^2/day. As expected, the surface nitrification rate in the 2nd aerobic stage was lower than that observed in the 1st aerobic stage because of the limited nitrifier populations in the 2nd aerobic stage as supported by the low ammonia loading.

A "biofilm" thickness of approximately 0.46 mm was estimated using a liquid volume displacement method by submerging the media with and without biomass into a water tank and comparing the displaced liquid volumes. The actual biofilm could be much thinner due to its high water content after a 10-minute drainage procedure before submerging in this study. The attached dry biomass growth was measured to be 22.6 g/m^2 on the structured sheet media, which was higher than those observed with free-floating media (8-12 g/m^2) in a similar pilot study (Johnson *et al.*, 2004). Other studies have reported a surface biomass concentration range of 10-35 g/m^2 for various media, depending on the specific organic and ammonia loadings (Jones *et al.*, 1999, Von Much *et al.*, 2000, Mass *et al.*, 2003, Rutt *et al.*, 2006, Stricker *et al.*, 2007). Although the structured sheet media tends to grow thin biofilm/boundary layer as a result of the dedicated aeration/water shearing with "smooth" surface of the media for enhanced oxygen and substrate mass transfer, the attached biomass growth indicates that the biomass on the structured sheet media may have a higher density, when compared to other media. This is also consistent with the reported observation that nitrification biofilm on the PVC surface had higher biomass density as a result of higher turbulent intensities (Kugaprasatham *et al.*, 1992)

Impacts of Residual D.O. and Soluble COD in the Structured Sheet Media IFAS System

The residual D.O. concentration in the aerobic tanks averaged 3.0 mg/L throughout the structured sheet media testing, which was adequate for process aeration and mixing. This appeared to be lower than other media systems (Johnson *et al.*, 2004, Choi *et al.*, 2007, Gellner *et al.*, 2008), which may be due to the enhanced oxygen transfer efficiency with the structured sheet media system.

A correlation analysis between residual D.O. and NH_3-N removal rate revealed that the nitrification rates increased as residual D.O. increased for both structured sheet media IFAS and activated sludge systems, which was consistent with other observations (Johnson *et al.*, 2002). However, the comparison between structured sheet media IFAS and activated sludge systems shows that increased aeration had a more positive impact on the nitrification performance of structured sheet media IFAS than activated sludge process (Figure 13). This could be rationalized that the diffusion of oxygen into the biofilm on the media was more easily limited by the residual D.O. concentrations in the system, as compared to the oxygen diffusion into the floc in an activated sludge system (Hem *et al.*, 1994).

Figure 14 shows the effects of soluble COD loadings on the nitrification performance of the structured sheet media IFAS system. A decrease in the ammonia removal rate was observed as the soluble COD loading increased and nitrification essentially became insignificant at a soluble COD loading greater than 105 ppd/kcf. It has been well documented that heterotrophic bacteria can overgrow autotrophic nitrifiers and reduce the ammonia removal efficiency at higher soluble COD concentrations (Ryhiner *et al.*, 1994, Hem *et al.*, 1994, Randall and Sen, 1996).

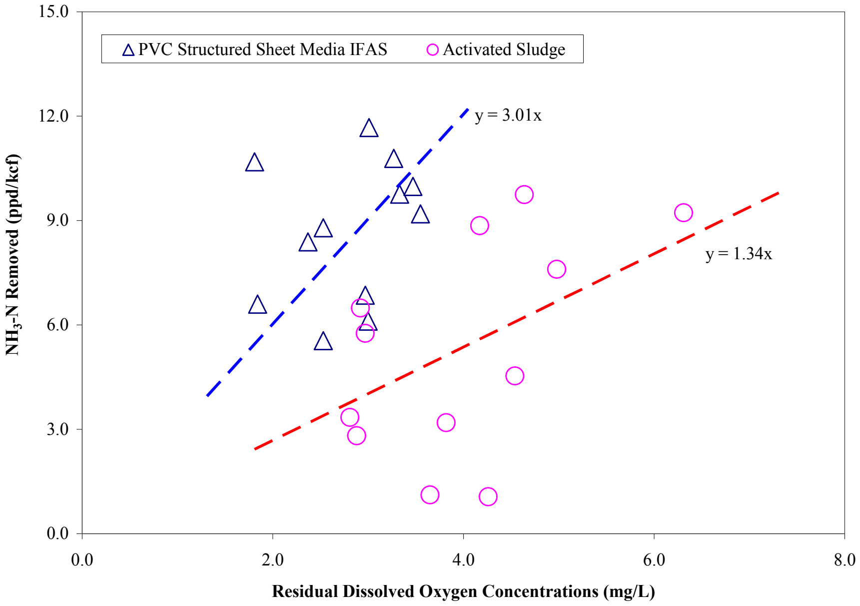


Figure 13 Effect of residual D.O. on the nitrification performance of PVC structured sheet media IFAS and activated sludge systems

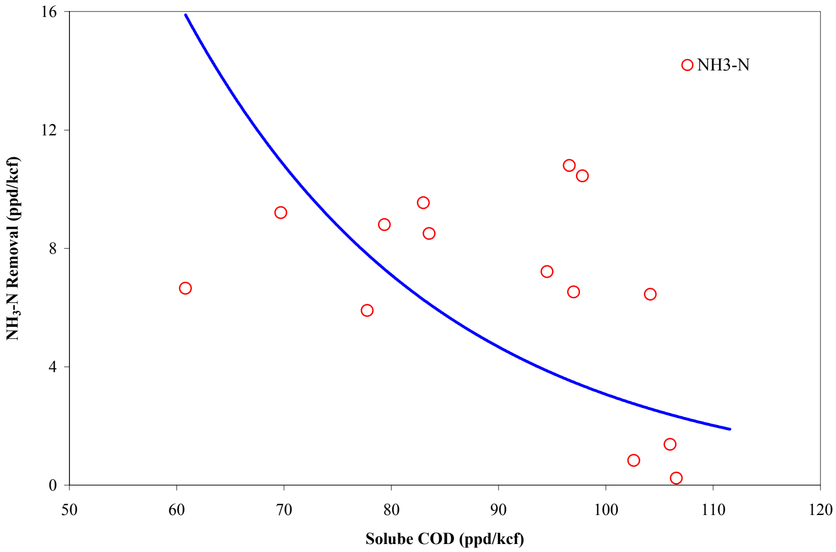


Figure 14 Impact of soluble COD loadings on the ammonia removal rates in the aerated PVC structured sheet media IFAS system

Total Nitrogen Removal in the Structured Sheet Media IFAS System

The pilot aerobic structured sheet media IFAS system coupled with anaerobic and anoxic stages was able to achieve an effluent TN of approximately 6.0 mg/L. Figure 15 shows average ammonia and nitrate concentrations at each stage of the pilot facility. The analysis of nitrogen mass balance suggests a fraction of nitrate was also reduced in the aerobic stages through the mechanism of simultaneous nitrification and denitrification (SND), presumably due to the presence of oxygen gradients in the biofilm and suspended bacterial flocs (Barnard *et al.*, 2004). Considering the dilution of RAS and IMLR, it was estimated that approximately 1.5 and 0.5 mg/L of TN was removed in the 1st and 2nd aerobic tanks, respectively, indicating a stronger SND activity associated with the first aerobic stage. This could be attributed to the possible thicker heterotrophic biomass growth on both attached and suspended phases at a higher organic/ammonia loading in the 1st aerobic tank, creating significant oxygen gradients for an elevated SND.

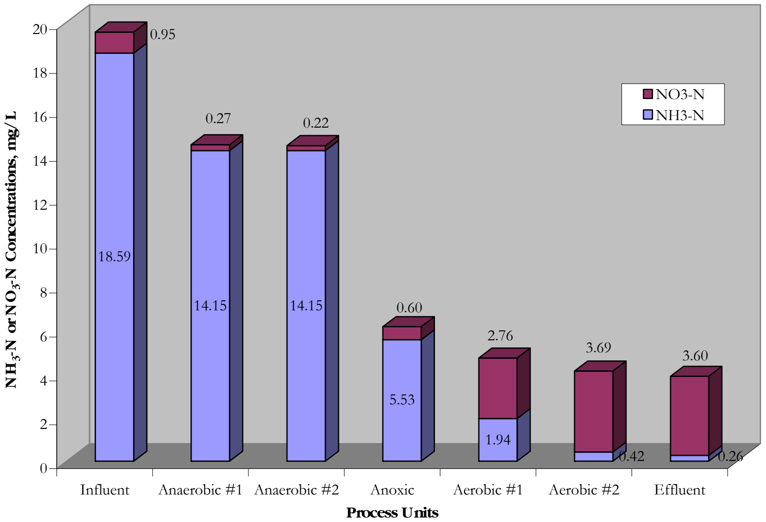


Figure 15 Average ammonia and nitrate profile across the pilot system

CONCLUSIONS

This pilot study has demonstrated that structured sheet media IFAS is capable of achieving complete nitrification to meet stringent nutrient limits. The dedicated aeration system underneath the media creates a unique shearing pattern along the "smooth" surface of the structured sheet. This promotes thin biofilm and boundary layers for enhanced oxygen transfer efficiency and effective nitrification and also eliminates the potential for red worm growth. A surface nitrification rate of approximately 0.88 g NH_3-N/m^2/day was obtained with structured sheet media at an average ammonia loading of 14.5 lbs/day per 1,000 ft^3 tank volume and an operating D.O. concentration of 3.0 mg/L. The measured biomass on the structured sheet media (22.6 g biomass/m^2) at low organic and ammonia loadings in the 2nd aerobic stage was comparable with reported values for other media, indicating potentially high-density biofilm growth associated with this media. It was also observed in the pilot study that red worms tend to proliferate in fabric media and the system can essentially lose nitrification completely when red worms are present.

The findings from the pilot study may have important implications for full-scale designs. First, the thin biofilm/boundary layer and its enhanced oxygen transfer efficiency may enable the structured sheet media IFAS to be operated at a relatively low residual D.O. (e.g. 3.0 mg/L in this study) although the aeration system should be also evaluated for sufficient mixing. Second, the surface nitrification rate of structured sheet media obtained from this study should be used with caution for design purposes as they are contingent on specific NH_3-N loading, D.O., soluble

COD, and other chemistry from the A^2/O process. Third, the results from the pilot study can be used to calibrate simulation modeling tools, specifically for structured sheet media, for an optimized full-scale process design. Finally, fine bubble diffusers can be used in a structured sheet media system for adequate mixing (as a result of distributed airlift pumping through media) and improved oxygen transfer efficiency over coarse bubble diffusers as typically used in a dispersed media system.

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