MATHEMATICAL MODELING AND EVALUATION OF IFAS WASTEWATER TREATMENT PROCESSES FOR BIOLOGICAL NITROGEN AND PHOSPHORUS REMOVAL

By

Tongchai Sriwiriyarat

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Clifford W. Randall, Ph.D., Chair
John T. Novak, Ph.D.
Daniel L.Gallagher, Ph.D.
John C. Little, Ph.D.
Peter Dold, Ph.D.

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Blacksburg, Virginia Tech

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(ABSTRACT)

The hybrid activated sludge-biofilm system called Integrated Fixed Film Activated Sludge (IFAS) has recently become popular for enhanced nitrification and denitrification in aerobic zones because it is an alternative to increasing the volume of treatment plant units to accomplish year round nitrification and nitrogen removal. Biomass is retained on the fixed-film media and remains in the aerobic reactor, thus increasing the effective mean cell resident time (MCRT) of the biomass and providing the temperature sensitive, slow growing nitrifiers a means of staying in the system when they otherwise would washout. While the utilization of media in aerobic zones to enhance nitrification and denitrification has been the subject of several studies and full-scale experiments, the effects and performances of fixed film media integrated into the anoxic zones of biological nutrient removal (BNR) systems have not adequately been evaluated as well as the impacts of integrated media upon enhanced biological phosphorus removal (EBPR). Also, user-friendly software designed specifically to simulate the complex mixture of biological processes that occur in IFAS systems are not available. The purpose of this research was to more fully investigate the effects of integrated fixed film media on EBPR, to evaluate the impacts of media integrated into the anoxic zone on system performance, and to develop a software program that could be used to simulate the effects of integrating the various types of media into suspended growth biological nutrient removal (BNR) systems. The UCT type configuration was chosen for the BNR system, and Accuweb rope-like media was selected for integration into the anoxic zones of two IFAS systems. The media also was integrated into the aerobic reactors of one of the systems for comparison and for further investigation of the performance of the Accuweb media on enhanced nitrification and denitrification in the aerobic zones. The experiments were conducted at 10 day total MCRT during the initial phase, and then at 6 days MCRT for the experimental temperature of 10 ^{o}C. A 13 hour hydraulic retention time

(HRT) was used throughout the study. A high and a low COD/TP ratio were used during the investigation to further study the effects of integrated media on EBPR. The PC Windows based IFAS program began with the concepts of IAWQ model No. 2 and a zero-dimensional biofilm model was developed and added to predict the IFAS processes. Experimental data from the initial study and existing data from similar studies performed at high temperatures (>10^{o}C) indicated that there were no significant differences in BNR performances between IFAS systems with media integrated into the anoxic and aerobic or only aerobic zones and a suspended growth control system maintained at the same relative high MCRT and temperature values. Even though greater biological nitrogen removal could not be achieved for the experimental conditions used, the experimental results indicated that the IFAS systems with fixed film media installed in the anoxic zone have a greater potential for denitrification than conventional BNR systems. As much as 30 percent of the total denitrification was observed to occur in the aerobic zones of the system installed the media only anoxic zones and 37% in the system with integrated media in both anoxic and aerobic zones where as no denitrification was observed in the aerobic zones of the control system when the systems were operated at 6 days MCRT and COD/TP of 52. It is statistically confirmed EBPR can be maintained in IFAS systems as well as Control systems, but the IFAS processes tend to have more phosphorus release in the anoxic zones with integrated fixed film installed. Further, the combination of split flow to the anoxic zone and fixed film media in the anoxic zone resulted in the decreased EBPR performances in the IFAS system relative to the control system.

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CHAPTER 1: INTRODUCTION

As a consequence of nutrient discharges from point and non-point sources, eutrophication and algae blooms become accelerated and stimulated in water bodies, which ultimately results in water pollution problems and the destruction of aquatic life. Processes for the removal of nutrients, mainly nitrogen and phosphorus, from wastewaters using 'biological nutrient removal' (BNR) processes, have been developed to reduce the impacts of nutrients from point sources.

One of difficulties for biological nitrogen removal in temperate zones is to accomplish year around nitrification, i.e. throughout the winter, because the nitrifiers, which oxidize ammonia to nitrate, are highly temperature sensitive slow growers and the volumes of the existing wastewater treatment plant units frequently are not large enough to maintain the biomass 'sludge retention time' (SRT) necessary for their retention in the system. To obtain nitrification on a year round basis in the suspended growth systems, it is necessary to increase the SRT to prevent nitrifier washout, but this may result in overloading of the secondary clarifier. Consequently, either the size of the aerobic bioreactor has to be increased or additional clarifiers have to be constructed, or both, and the aeration system may have to be improved. However, construction of new treatment facilities such as aerobic tanks or clarifiers may be limited by space or budget. Therefore, it becomes desirable and sometimes necessary to find alternative options to resolve the upgrade problems.

Traditionally, either a suspended growth activated sludge system or an attached growth fixed film system was selected for the biological treatment process of wastewater treatment plants. Both processes provide distinctly different advantages and disadvantages. The attached growth system typically is simpler to operate and provides more stable treatment at lower operating costs compared to the suspended growth activated sludge system, but the activated sludge system typically provides a greater removal of BOD. When operated with a low loading rate, fixed film systems also can be operated without the need to separate biomass and treated effluent, i.e., without a secondary clarifier, whereas the secondary clarifier is an essential component of activated sludge system. However, greater flexibility and better effluent quality typically can be obtained using activated sludge systems. The two systems usually have been operated as stand

alone biological processes, but are sometimes operated in series by coupling fixed film processes such as trickling filters or rotating biological contactors (RBC) with an activated sludge system. More recently, fixed-film media have been integrated into activated sludge reactors for operation as integrated fixed film activated sludge (IFAS) systems, also known as hybrid systems.

The hybridization of activated sludge and fixed film systems has been proposed as a potential method to overcome treatment problems without additional construction because nitrifiers attached to integrated media will have a longer solids retention time (SRT) within the system and, therefore, have higher biomass concentration than the suspended growth nitrifiers alone. Thus, the systems can both maintain and supplement nitrification without significantly increasing the solids loading on the final clarifiers. In the United States, IFAS pilot-scale systems have been extensively demonstrated by Virginia Tech researchers to study enhanced nitrification with simultaneous COD removal at low temperature and MCRT. The studies were extended to include investigation of different media types, media location in the aeration basin, operating MCRT, temperature, and nitrification and denitrification efficiencies (Mitta, 1994; Sen and Randall, 1994; Jensen, 1995; Sen, 1995; Liu, 1996). The performances of integrated Ringlace and Captor sponges in full-scale treatment plants were evaluated at the Annapolis and Cox Creek Plants, respectively, in Anne Arundel County, Maryland, USA, (Randall and Sen, 1996). However, none of these studies involved investigation of enhanced biological phosphorus removal (EBPR) in conjunction with IFAS.

It is known that biomass must be subjected to alternating anaerobic and aerobic conditions to accomplish practical enhanced biological phosphorus removal (EBPR). This is because the biomass needs to uptake short chain volatile fatty acids (SCVFAs) and release phosphorus to the bulk liquid to accumulate Polyhydroxyalkanoates (PHA) under anaerobic conditions, and then utilize the stored PHA and uptake phosphorus under subsequent anoxic or aerobic conditions to accomplish EBPR. However, IFAS systems are operated as continuous flow systems and the fixed-film media typically remains in one reactor and does not circulate through different environmental conditions. Consequently, it would seem that the fixed film biomass would not accomplish EBPR, and only the suspended biomass would be involved. This could result in a substantial reduction of the EBPR potential of IFAS systems compared to suspended growth

activated sludge BNR systems. The question is, can hybrid systems provide sufficient EBPR to meet most phosphorus removal requirements for municipal wastewaters.

It is possible that fixed film media in the anoxic zone of a BNR system can enhance COD removal and denitrification in addition to enhanced nitrification and denitrification in the aerobic zones. There have been studies that integrated fibrous carriers into the anoxic tank at low temperature (10-15 ^{o}C) performed in the Netherlands (Liu et al., 1996), studies with rotating biological contactors (RBC) integrated into both anoxic and anaerobic tanks, plus partially submerged into the aerobic tanks (Su and Ouyang, 1996), and submerged RBCs in an intermittently aerated (aerobic/anoxic) tank in Korea (Kim et al., 1999). However, no attempt has been made to specifically evaluate the biofilm process in the anoxic tanks.

A mathematical model has been developed for a multi-cell activated sludge system with integrated biofilm support media by Sen (Sen, 1995; Sen and Randall, 1996) to predict carbonaceous removal and nitrification. The model simulation was based on empirical equations for the attached growth and steady state theoretical equations for the suspended growth, and was implemented by a spreadsheet program. Subsequently, a steady state IFAS computer program, which combines the IAWQ mechanistic model (Barker and Dold, 1997) and Sen's empirical equations, was developed to simulate the IFAS wastewater treatment processes (Sriwiriyarat, 1999). However, the calibration process was conducted only for the UCT/VIP plant configuration with sponge-type media in the aerated zone for enhanced nitrification and COD removal using data from the pilot plant research of Sen and co-workers. This model does not include the denitrification process carried out by fixed film biomass in the aeration reactors due to a lack of empirical equations. Similarly, a simulation model has been developed in Japan to support a combined activated sludge and biofilm process for nitrogen and phosphorus removal by the so-called CAB/NP process. The detachment mechanisms were integrated into the ASM model with a transport mechanism because the movement of detached biofilm to suspended growth was a key concept of this model. Polyurethane plastic media was selected as a media carrier for this process. The simulation was conducted using the AQUASIM program (Suzuki, 1999).

Hybrid activated sludge-fixed film media systems have been the subject of considerable research and development in recent years, but accepted design methodology has not been fully developed. The purpose of this research was to more fully investigate the following topics.

1. Evaluation of IFAS wastewater treatment processes at high MCRTs and temperatures.
2. The effects of anoxic media for denitrification in IFAS BNR wastewater treatment systems.
3. The performance of IFAS wastewater treatment processes for biological phosphorus removal.
4. Mathematical modeling of biological nutrient removal in IFAS wastewater treatment processes.

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CHAPTER 2: REVIEW OF LITERATURE

2.1 Biological Nutrient Removal (BNR)

Biological Nutrient Removal (BNR), i.e., combined biological nitrogen removal and biological phosphorus removal, is a biological method to reduce the impact of point source nutrient discharges on the oxygen content of receiving waters. It is well known that one of the effects of nutrient discharges into the water bodies is the oxygen demand for biodegradation of algae biomass that accumulates in the bottom sediments as a result of algae biomass production. Considering that the average composition of algae biomass is $C_{106}H_{263}O_{110}N_{16}P$, one kilogram of bioavailable phosphorus has the potential to produce 111 kilograms of algae biomass, which will have a COD of 138 kilograms. For the same stoichiometric formula, a kilogram of nitrogen could potentially produce 16 kilograms of algae with a COD equivalency of 20 kilograms. Typical raw municipal wastewater contains 6-8 mg/L of phosphorus (P) and 24-40 mg/L nitrogen (N), and about 400-500 mg/L COD, while treated effluents without nutrient removal typically contain 4-6 mg/L P and 18-30 mg/L N. Therefore, the COD production potential for effluent P is 552 – 828 mg/L, and for effluent N is 360-600 mg/L, oxygen demand equivalencies that are nearly equal to or greater than that of raw sewage, depending upon which nutrient limits algae growth. This COD accumulates in the sediment, resulting in high sediment oxygen demands and conditions detrimental to desired aquatic life.

It has been demonstrated that BNR is an economical nutrient removal method that provides economical and environmental benefits typically greater than conventional activated sludge treatment plants that incorporate chemical or physical nutrient removal processes (Randall, 1992; Randall, 1997). The energy required for aeration can be reduced by both enhanced biological phosphorus removal (EBPR) and biological nitrogen removal due to COD substrate stabilization in the anaerobic and anoxic zones, respectively. Typically, 50% or more of the aeration energy required for complete nitrification can be recovered by using the influent COD for denitrification. Depending on the characteristics of the process influent wastewater and the required effluent phosphorus standards, chemical additions for phosphorus removal and alkalinity adjustment may not be needed if EBPR is implemented (Randall, 1992). Biological

nitrogen removal consists of two biochemical processes. The first process is nitrification, which converts ammonia nitrogen to nitrate nitrogen, which does not utilize COD substrate, but consumes dissolved oxygen (DO) and alkalinity. The second process, called denitrification, involves the reduction of nitrate to gaseous molecular nitrogen in the absence of DO. Denitrification utilizes COD substrate as stated previously and produces alkalinity up to 50 percent of what was consumed during nitrification

The EBPR process involves the accumulation of short-chain fatty acids (SCFA) in the microbial cells under anaerobic conditions as poly-β-hydroxyalkanoates (PHA), resulting in the release of phosphorus into the bulk solution. Those stored PHA are subsequently used for energy and growth purposes under anoxic and aerobic conditions where appropriate electron acceptors available. The released phosphorus is taken up by microorganisms during this step to store excess energy following growth and maintenance.

2.2 Integrated Fixed Film Activated Sludge (IFAS)

An activated sludge wastewater treatment process configuration has been recently applied in the United States is the Integrated Fixed Film Activated Sludge (IFAS) process, which combines activated sludge and biofilm processes to upgrade the wastewater treatment plants for COD removal and advanced nutrient removal. This technology merges the main advantages of both biofilm processes and activated sludge processes into one process by integrating fixed-film media into activated sludge. The attached growth system provides a high volumetric density of microorganisms by natural attachment on the media, thereby increasing the mean cell retention time (MCRT), while reducing the mixed liquor suspended solids (MLSS) concentration which flows to the secondary clarifiers. This reduces or resolves secondary clarifier overloading, and benefits COD removal and nitrification. The large amount of biomass on the integrated media also adds stability of the biological system by reducing shock load and toxic load problems, and by providing a longer MCRT for the nitrifiers. Properly designed and operated suspended growth systems typically provide greater flexibility and better effluent quality than fixed-film systems, so the combination enhances both processes. IFAS processes have been extensively studied for enhancement of nitrification and denitrification in aerobic zones.

Many media types have been investigated for their ability to enhance nitrification and biological nitrogen removal in the aerobic zones of IFAS systems. For example, in a study in Japan, 8 cm^3 polyurethane foam cubes were used as integrated fixed-film media in a complete mix series of reactor to treat municipal wastewater. The results showed that the resulting nitrification rate was 0.33 mg/hr/cube at a temperature of 15 ^oC when media empty reactor volume ratios of 10% and 20% were used (Tsuno, 1992). Attached media chosen on the basis of diffusion capacity were added to a full-scale system operated with intermittent anoxic/aerobic conditions to attain simultaneous BOD and nitrification with a media fill volume fraction of 30%. This system obtained effluent BOD and nitrogen concentrations of 20 mg/l and 15 mg/l, respectively, over the temperature range of 13-30 ^oC (Kondo, et al., 1992). In Germany, Ringlace© , a rope-like media with many ringlets to increase specific surface areas, was installed in the wastewater treatment plant of the city of Geiselbullach to upgrade the facilities to achieve year round nitrification and to improve sludge settlings (Lessel, 1991; Lessel, 1993). Linpor-N©, a sponge-type media, was integrated as a last step treatment without subsequent clarification to enhance more nitrification by Morper and Wildmoser, 1989. They observed at least 50% nitrogen removal in this system for temperatures as low as 10 ^oC). In the USA, Captor©, another sponge-type media, was used at the Moundsville, West Virginia WWTP to improve nitrification and nitrogen removal (Golla et al., 1991). The resulting system obtained average nitrogen removal of 70-75% in the IFAS zone and average effluent ammonia nitrogen concentrations of 5.4 mg/L (Golla et al., 1993). Full-scale Modified Ludzack Ettinger (MLE) and Step Feed BNR IFAS configurations utilizing Ringlace© were installed and evaluated side-by-side with a control system at the Annapolis, Maryland, WWTP, operated by Anne Arundel County. The performance data showed that nitrogen removal in the IFAS sections were up to three times higher than the control sections in which no media was integrated. The experiment results also indicated that the both configurations provided more denitrification in the aerobic zones than the corresponding control sections, and that the step feed configuration outperformed the MLE configuration (Sen et al., 1993; Sen et al., 1994; Sen 1995; Randall et al., 1996; Randall, 1997).

Extensive investigations have been made of the effects of media types, media location, operating MCRT, temperature, and nitrification and denitrification in the aerobic zones in pilot-scale systems located at Virginia Tech, Blacksburg, USA. The results indicated that Captor© sponges

significantly increased nitrification at a temperature of 12 ^{o}C for operating aerobic MCRTs over the range of 1.7-3.4 days. More enhanced nitrification was observed in the systems with Captor© media than those with Ringlace© media. In contrast, more enhanced denitrification was observed in the aerobic zones containing Ringlace© media compared to Captor© media (Mitta, 1994; Jensen, 1995; Sen, 1995; Liu, 1996). Soluble biodegradable COD ($SCOD_{bio}$) concentrations above 10 mg/L in the media zones were found to be detrimental to nitrification (Tsuno, 1992; Sen, 1995).

In addition to enhanced nitrification and denitrification in the aerobic zones, it is possible that fixed film in the anoxic zones of BNR systems would enhance COD removal and denitrification resulting in lower effluent total nitrogen. The potential of using fixed film media for denitrification in anoxic reactors before an oxidation ditch was evaluated in Delft, the Netherlands, using fibrous carriers as the fixed-film material (Hao et al., 1995). Denitrification using endogenous respiration and then an external COD substrate was evaluated in the first experimental run. The comparison between a system with packing material and a system without fibrous carriers were conducted in the second run. The denitrification rate in the system with packing material and unlimited external substrate increased continuously as the nitrate loading increased over 20 g NO_x^-/(kg VSS/day). Enhanced biological phosphorus removal was not incorporated into this study. There was also another study in The Netherlands with a BNR system integrated with fibrous carriers in the anoxic tank receiving sewage wastewater most of the time at low temperatures (10-15 ^{o}C). In this study, partial influent flow was redirected to an anaerobic tank for phosphorus release, but was subsequently replaced by chemical precipitation (Liu et al., 1996a). In this study, the system accomplished over 90% denitrification efficiency when the loading rate of the oxidized nitrogen was less than 0.4 kg/m^3.d. However, no attempt was made to specifically evaluate the biofilm process in the anoxic tank or to evaluate the effect of IFAS media on EBPR. Additionally, the fibrous carriers were used for the anoxic zone preceding an activated sludge system in China called SBF-AF in which there was no returned mixed liquor activated sludge to the biofilm reactor so the anoxic reactor was only a biofilm reactor. In addition, EBPR was not included in this system and it was investigated at high temperature (20-30 ^{o}C), HRT (16-22.9 hrs), and SRT (50 days) (Liu et al., 1996b). The denitrification rate decreased when the NO_x-N loading rate was greater than 0.7 kg NO_x-

$N/m^3/day$. Rotating biological contactors (RBC) can also be used as integrated support media and have been evaluated by Su and Ouyang (1996) in Taiwan, and Kim et al. (1999) in Korea. Su and Ouyang (1996) applied fully submerged RBCs in the anaerobic and anoxic reactors, and partially submerged RBCs in the aerobic reactors. It was shown that high degrees of nutrient removal could be accomplished using this system. Intermittent aeration in the aerobic tank with incorporated submerged RBCs, and preceded by an anaerobic tank was studied in Korea by Kim et al. (1999) to investigate the performance of this system for biological nutrient removal. The system was operated at different: influent BOD concentrations, oxic/anoxic time ratios, and the number of intermittent aeration (NIA) cycles per day. The results indicated that the total nitrogen removal efficiencies mainly depended on the oxic/anoxic time ratio and influent BOD concentration. As BOD concentration increased, the total oxic time per day had to be increased to maintain nitrification, but the total anoxic time needed to achieve maximum total nitrogen removal efficiency decreased (Kim et al., 1999). In Japan, the comparison between a system with media integrated into the anoxic reactor and one without media was conducted using hollow polypropylene pellets and a temperature of 15 ^oC. They reported that integrating fixed film media could result in higher denitrification and ammonification providing higher nitrogen removal efficiency (Takizawa et al., 1996).

Theoretically, enhanced biological phosphorus removal (EBPR) by attached biomass would not be possible as they are fixed in one location, unless the environmental conditions in the reactor was changed to allow the biofilm to experience alternating anaerobic and oxic conditions. Sequencing Batch Reactors (SBRs) are systems that operate in this manner and can be used to accomplish EBPR. The performance of EBPR in SBR IFAS systems was studied using a 1000 L reactor filled with Pall-Rings as biofilm support, which provided a total surface area of 54 m^2. Performance was evaluated by applying seven different organic loadings, cycle durations, and aerobic HRTs. The results indicated that the highest removal rates for COD removal, nitrification, and EBPR could be obtained when the organic loading was 3 $gCOD/m^2/day$ at 24 hours cycle duration with an anaerobic/aerobic ratio of 1.0/1.0. The organic loading rate was maintained under 5 $gCOD/m^2/day$ to achieve EBPR (Garzon-Zuniga and Gonzalez-Martinez., 1996). Helness and Ødegaard (1999) carried out the experiments with EBPR in a moving bed biofilm SBR. In their study, 53% of a 10 L SBR was filled with KMT-media and fed with varied

loading rates of acetate, ammonia, and phosphorus in the synthetic wastewaters. They concluded that good and stable EBPR could be achieved when the length of the anaerobic period was long enough to completely remove the readily biodegradable COD and at the same time the COD loading rates must be enough for growth of biomass in the reactor.

2.3 Mathematical Wastewater Modeling

Many biochemical reactions and organic compounds are involved in the processes that occur in biological nutrient removal systems as compared to systems designed for only organic compound (BOD) removal. The additional reactions include nitrification, denitrification and excess biological phosphorus removal; therefore, mathematical models as a tool to simplify the complexity of such processes become necessary to optimize the process designs or to troubleshoot problems at wastewater treatment plants as well as at the bench-scale in research. The models are generally required to be more practical for engineering applications while they are more flexible for research tools. The mathematical models are mainly divided into two major categories according to biological growth processes, i.e., suspended growth or attached growth. However, models may expand to include both types of these biological growths into one model such as an IFAS model.

2.3.1 Activated sludge modeling

Many mathematical models have been developed to describe various sophisticated activated sludge systems, based on the model initiated by the task group formed by IAWQ (reference), for designing and operating activated sludge systems. One such model was the single sludge system model developed by Grady (1986). This model consisted of seven processes including carbon oxidation, nitrification, and denitrification, and was based on the modeling concept proposed by the IAWQ task group. This effort was followed by the development of SSSP computer software (Bidstrup, 1988). The IAWQ task group, which included Grady, developed and published a single sludge model that was designed Activated Sludge Model No. 1 (ASM1) (Dold and Marais, 1986; Henze et al., 1987). ASM1 does, however, not include the enhanced biological

phosphorus removal (EBPR), but a later model that included EBPR was proposed and developed by IAWQ and called ASM2 (Henze et al., 1994). An additional advancement was made by Barker and Dold (1997) when they included the anoxic growth of Poly-P microorganisms into the general activated sludge model that had been primarily developed at the University of Cape Town after the of existence of denitrifying dephosphatation was indicated by research efforts. Anoxic and anaerobic hydrolysis of slowly enmeshed biodegradable COD processes also were incorporated into this model as well as the fermentation of readily biodegradable organic materials. The general model is based on the original ASM1 and the Wentzel Model (1989). Henze (1999) proposed ASM No. 2d that includes phosphorus removal by Poly-P microorganisms during denitrification. Gujer (1999) presented ASM No. 3, which is a modification of ASM No. 1. A substrate storage process was introduced into this version as a new process and it is assumed that there is no COD flow from nitrifier decay. The modeling of heterotrophic and autotrophic decay processes was clearly separated in ASM3.

2.3.2 Biofilm modeling

Early biofilm mathematical models focused on substrate utilization in the biofilm, which was described as a process of molecular diffusion and simultaneous biochemical reactions (Williamson and McCarty, 1976). Numerous steady state models have been developed, which vary from single microorganism specie to multiple-species and from a single substrate to multiple-substrates. Subsequently, a steady state biofilm model of a single substrate coupled with substrate flux into the biofilm was developed by assuming neither net growth nor decay over time, and a minimum substrate in the bulk liquid which must be maintained to achieve a steady state condition. The Monod equation is typically used to describe the biochemical reactions and Fick's law is used to describe diffusion, resulting in equations for the basic mechanisms in biofilms. Idealized biofilms have been described as having uniform cell density and uniform thickness with excess concentration of all nutrients required for growth. The model was evaluated and the results showed that the model successfully predicted the substrate utilization rate and biofilm thickness.(Rittmann and McCarty, 1980). Mass transport by diffusion is assumed to be

one dimensional because the biofilm is typically very thin. Due to the possibility of extensive computational efforts, steady state mechanistic models with multiple-species and competition of substrate and space were developed. A multi-species model for COD removal and nitrification was proposed by Wanner and Gujer, but this model was not verified with experimental data. They showed that given the competition for oxygen, the heterotrophs may be washed out at low substrate concentration. In contrast, at high substrate concentrations, they may overgrow the slow-growing autotrophic organisms, causing them to wash out. The heterotrophs have a tendency to reside at the surface and autotrophs may accumulate more in the deeper layers. The biomass flux was used to simulate biomass growth. However, this model is not a true steady state model (Wanner and Gujer, 1985). Subsequently, Rittmann and Manem (1992) presented a steady state model that described multi-species behavior with multiple active species, inert biomass, substrate utilization, and diffusion within the biomass, external mass transport, and the biofilm detachment phenomenon. This model was verified experimentally and its predictions agreed with the observed data in terms of space competition. Higher acetate concentrations resulted in NH_4^+N flux decrease because autotrophs were forced deeper into the biofilm by heterotrophs.

2.3.3 IFAS Modeling

To support the IFAS experiments, a mathematical model including necessary basic activated sludge processes and empirical equations was developed (Sen, 1995; .Sen and Randall, 1996). The empirical equations were developed by batch tests from which the kinetic coefficients were determined by nonlinear regression approach. Double Monod expressions were used to express COD uptake and nitrification by the biofilm from the maximum uptake rates for DO, biodegradable soluble COD, and ammonia nitrogen in the mixed liquor. The simulations were conducted using a spreadsheet program and the results compared with the experimental data. The predictions were fitted quite well with the aerobic phase experimental data. The predictions were higher than experimental data in the anaerobic and anoxic phases because only basic processes were used in the model. These problems were solved by Sriwiriyarat (1999) by including the complex activated

sludge processes from IAWQ and wastewater characterization. User-friendly and interactive computer software also was developed to replace the spreadsheet version. The biological phosphorus removal processes were not included in Sen' s mathematical model, but were incorporated into Sriwiriyarat's computer software. However, predictions were not made because of a lack of experimental data and calibrated kinetic and stoichiometric parameters. Similarly, a simulation model has been developed in Japan to support a combined activated sludge and biofilm process for nitrogen and phosphorus removal by the so-called CAB/NP process. For this model, biofilm processes and detachment mechanisms were integrated into ASM Model 2. A transport mechanism for the movement of detached biofilm to suspended growth was a key concept of this model. Polyurethane plastic media was selected as a media carrier for this process. The simulation was conducted using the AQUASIM program (Suzuki, 1999).

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CHAPTER 3: EVALUATION OF IFAS WASTEWATER TREATMENT PROCESSES AT HIGH MCRT AND LOW TEMPERATURES

T. SRIWIRIYARAT AND C.W. RANDALL*

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University, 418 Durham Hall, Blacksburg, VA 24061, USA

Abstract—

Suspended solids MCRT and temperature are two key parameters for designing Integrated Fixed Film Activated Sludge (IFAS) wastewater treatment processes, as an alternative for achieving year round nitrification. It has been demonstrated from both full-scale and bench-scale studies that IFAS can accomplish year-round nitrogen removal and denitrification in aerobic zones in winter when operated with suspended growth MCRTs less than the critical MCRT for nitrifiers, thus avoiding increasing reactor or clarifier volumes. The objective of this study was to investigate the performances of IFAS systems that were operated at relative high MCRT compared to nitrifier washout MCRT and low temperature for biological nutrient removal. The comparison between two IFAS systems with Accuweb© media in both the anoxic and aerobic zones, and a conventional three zone Biological Nutrient Removal (BNR) system was conducted at 10 ^{o}C with a 10 day MCRT using the UCT/VIP configuration for both systems and feeding with Blacksburg domestic wastewater. Influent flow was split 50% to the first anaerobic reactor and 50% to the first anoxic reactor to enhance denitrification in one of IFAS systems and the conventional BNR control system whereas 100 percent of the influent flow was fed to the first anaerobic reactor in the other IFAS system. Previous studies by Mitta (1995) with similar IFAS systems operated at moderate temperature and low MCRT (18 ^{o}C and 5.3 days MCRT) to simulate warm weather conditions were also reviewed in this study. He found no difference in nitrification between the IFAS and control systems, but the IFAS system obtained greater nitrogen removal. The data from this investigation indicated that the performances of the control and IFAS systems were insignificantly different under the experimental operating conditions for both biological nitrogen and biological phosphorus removal except for IFAS with integrated fixed film media in the anoxic zone and when 50 percent of the influent was added directly to the first anoxic reactor.

Keywords— Activated Sludge**,** IFAS, MCRT, BNR, Temperature, Nitrification, Denitrification, EBPR, Accuweb©

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*Corresponding author. E-mail: cliff@vt.edu; Fax: :(540) 231-7916

INTRODUCTION

The Integrated Fixed Film Activated Sludge (IFAS) process with biofilm support media in the aerobic zone has been demonstrated as an alternative design for biological nitrogen removal and as a cost-effect option for retrofitting wastewater treatment plant to sustain nitrification throughout the winter, without significantly increasing the suspended growth concentration, and, therefore, without increasing reactor or clarifier volumes (Randall et al, 1996; Sen et al, 1996). The observations from both bench-scale and full-scale studies reported that the enhanced nitrification and denitrification in the aerobic media section, resulting in the reduction of anoxic volume, could be obtained from even when the IFAS systems were operated at suspended solids MCRTs below the critical MCRT for nitrifying suspended solids systems (Liu, 1996; Mitta, 1994; Randall et al, 1996; Sen et al, 1996).

The IFAS wastewater treatment plants that are located in temperate zones experience seasonal changes in temperature throughout the year. During warm weather, when the growth rate of nitrifiers is high, the IFAS treatment systems are capable of accomplishing complete nitrification and BNR with only the suspended growth in the system, but the biofilm support media must be maintained in the system to be prepared for the upcoming winter. It is unknown what complications this causes for both enhanced biological phosphorus removal (EBPR) and total nitrogen removal during the summer. Unlike suspended growth biomass that endlessly cycles through anaerobic and subsequent anoxic or aerobic conditions of continuous flow system, the biofilm growth does not cycle and may not be able to contribute to EBPR. For example, it is possible that IFAS systems need to be operated at higher MCRTs than conventional systems during warm weather to maintain enough suspended solids to accomplish EBPR. The objective

of this investigation was to evaluate the BNR performances of IFAS systems when operated under conditions suitable for conventional BNR systems.

EXPERIMENTAL METHODOLOGY

Three UCT/VIP pilot-scale continuous-flow BNR activated sludge systems, two IFAS and one conventional suspended solids systems, were operated at Virginia Tech, Blacksburg, VA USA. Each system consisted of two anaerobic, two anoxic, and three aerobic reactors in series as shown in Figure 1, with the configurations listed in Table 1. System 1 was integrated with 0.3 ft^2 of 1 inch-type Accuweb© media in both anoxic reactors and 1.4 ft^2 in each of the first two aerobic reactors, while System 2 had 2.1 ft^2 of the same type media in aerobic reactors two and three. One square foot of 1 inch-type Accuweb© consists of 64 cells of which each cell can be extended linearly to 5.50 inches/cell resulting in a total of 352 inches/ft^2. Both IFAS systems were operated in parallel with the control system without media. All systems were operated at an HRT of 13±1 hours, a mixed liquor suspended solids (MCRT) of 10 days (after excluding the volume displaced by fixed film support media), and at a flow of about 175 L/day and a temperature of 10±1 ^oC. The Blacksburg wastewater was collected directly from the main sewer and stored in the building to equilibrate to the operating temperature for 24 hours before it was fed to the system. The strength of the sewage was increased to approximately 600 mg/L COD by adding a variable amount of sodium acetate, 70 mg N /L by adding urea, and 34 mg PO_4-P /L by adding KH_2PO_4. The additions resulted in a COD/TP ratio of 18 and a TKN/COD ratio of 0.12. The COD/TP ratio was selected so that COD was limiting and phosphorus would not be completely removed in the systems, thereby enabling determination of unrestricted phosphorus release and removal rates. During the experiments, pH was maintained between 7.0-7.5 in the anaerobic reactors of all three systems.

Table 1 System configuration and flow rate through cells for each system

Location	Condition			Effective Volume (L)			Media Location and Amount (ft2)			Flow Rate Through Cell (Q)			Wastage Flow (L/day)		
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control	IFAS1	IFAS2	Control
Cell 1	Ana 1	Ana 1	Ana 1	7.6	7.6	7.6	-	-	-	1.5Q	2.0Q	1.5Q	-	-	-
Cell 2	Ana 2	Ana 2	Ana 2	7.6	7.6	7.6	-	-	-	1.5Q	2.0Q	1.5Q	-	-	-
Cell 3	Anx 1	Anx 1	Anx 1	7.2	7.6	7.6	0.3	-	-	4.5Q	4.5Q	4.5Q	-	-	-
Cell 4	Anx 2	Anx 2	Anx 2	7.2	7.6	7.6	0.3	-	-	4.5Q	4.5Q	4.5Q	-	-	-
Cell 5	Aer 1	Aer 1	Aer 1	20.1	22.2	22.2	1.4	-	-	3.5Q	3.5Q	3.5Q	-	-	-
Cell 6	Aer 2	Aer 2	Aer 2	20.1	18.5	22.2	1.4	2.1	-	3.5Q	3.5Q	3.5Q	-	-	-
Cell 7	Aer 3	Aer 3	Aer 3	22.2	18.5	22.2	-	2.1	-	3.5Q	3.5Q	3.5Q	7.60	8.00	7.40
Cell 8	De-oxygenation			4	4	4									
Total Effective Volume (L)				96	93.6	101									

*Ana = Anaerobic, Anx = Anoxic, Aer = Aerobic, Q = Influent Flow

The systems were monitored for mixed liquor suspended solid (MLSS), mixed liquor volatile suspended solid (MLVSS), chemical oxygen demand (COD), anions (nitrite, nitrate, phosphate, and sulfate), and cations (ammonia-N, potassium, magnesium, and calcium). At steady state, influent and effluent Total Kjeldahl Nitrogen (TKN) and Total Phosphorus (TP) were also measured. MLSS, MLVSS, TKN, TP and COD were analyzed in accordance with Standard Methods for the Examination of Water and Wastewater, 19th Edition, 1995. Anions were analyzed using a Dionex 2010I ion chromatography (IC) with an IONPAC AS4A-SC column and electrochemical conductivity detector (Dionex Corp.,Sunnyvale, CA). Cations were analyzed using a Dionex 120 ion chromatography (Dionex Corp.,Sunnyvale, CA).

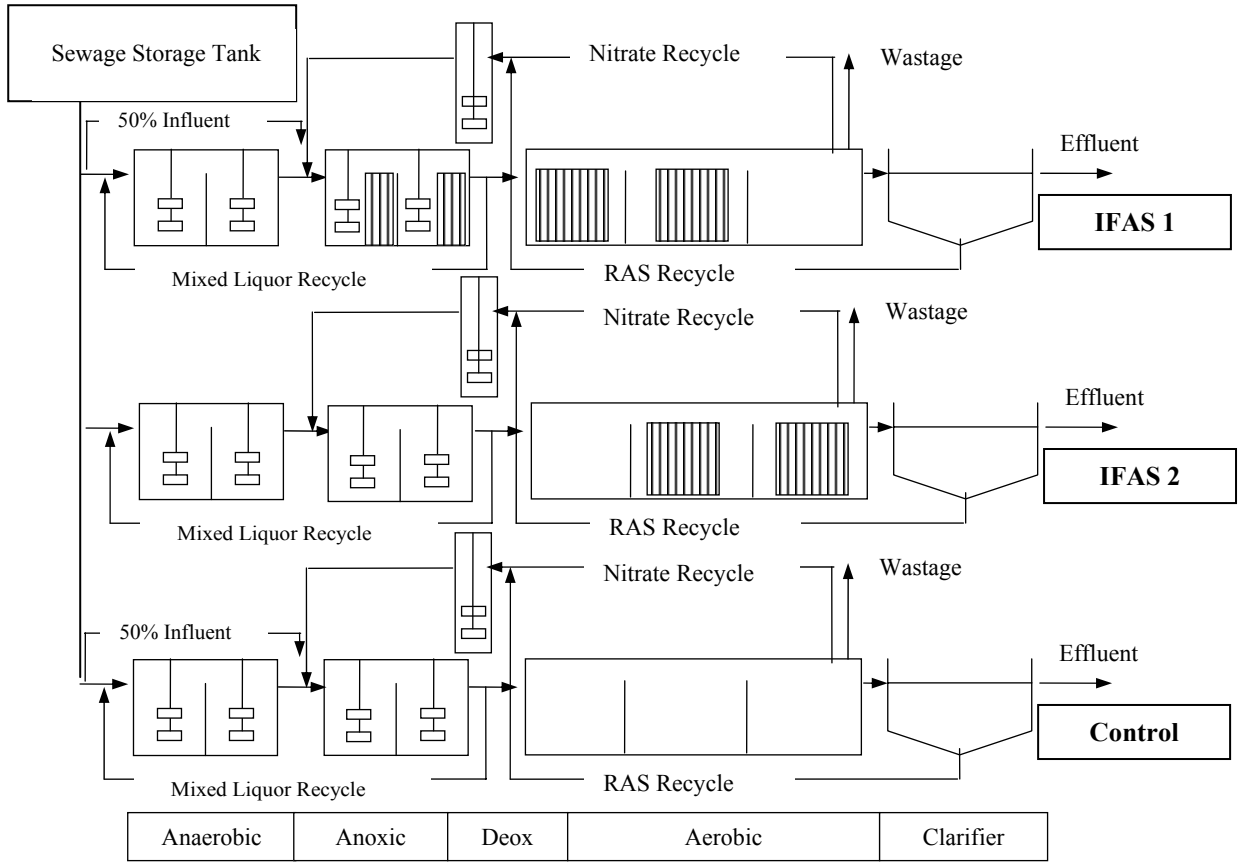


Figure 1. Schematic diagrams of the three systems used for the IFAS pilot-scale study

The growth on the media at steady state was measured by oven drying the media web taken from the anoxic and aerobic reactors at 105 ^{o}C for at least 24 hours after draining free water for 1 hour and determining the wet weight of the media web (A). The combined biomass and media web

were reweighed (B) and subtracted from the wet weight to determine the amount of water entrained in the web (A-B). After all dried biomass was removed from the media web, the weight of the media web was measured (C). The difference in weight (B-C) was considered to be the amount of dried biomass on the media web. Dried biomass samples were randomly selected and were ignited at 550 ^{o}C for 20 minutes in accordance with Standard Methods (APHA, 1995). The percentage of volatile solids was determined and was used to calculate the total volatile solids on the media web.

RESULTS AND DISCUSSION

The systems were operated and monitored for over 4 months to allow them to reach steady state conditions, and then four runs of steady state data were collected from each system to characterize each of them. The results, in Table 2, show that each system could equally remove an average of about 95 percent of the organic matter (COD), accomplish nearly 100 percent oxidation of ammonia nitrogen and about 75 percent total nitrogen, and 72 percent total phosphorus removal, except for the IFAS 1 system which could accomplish only 61 phosphorus percent removal efficiency. All systems were apparently under loaded with respect to nitrification, and received inadequate available COD for phosphorus removal to less than 10 mg/L. The average concentration and standard deviations are also included in Table 3.

The graphs in Figures 2 and 3 indicate that both IFAS systems and the control system could accomplish complete nitrification with or without media integrated into the activated sludge at 10 ^{o}C and operated at a 10 day MCRT. The total oxidized nitrogen in Table 4 also indicates that the same performances could be achieved from all systems during normal operations. To determine the nitrification rate and capacity of the acclimated biomass without ammonia limitation, the influent was spiked with urea to increase the influent TKN to 110 mg N/lL. The data in Table 4 compares the nitrification rates obtained during normal operation with the results when the influent was spiked with TKN. The experimental results show that all three systems were capable of greater nitrification than was being accomplished at steady-state conditions. It should be noted that the performance of the IFAS 1 system was less than other two, probably because there was a large population of red worms on the media installed in the aerobic reactors of that system. The highest nitrification rates in the control and IFAS 2 systems were observed

in the first aerobic cells, which did not contain media. In contrast in IFAS 1 system, nitrification was reduced in the first aerobic cell. This can be explained by the space competition between heterotrophic and autotrophic microorganisms and diffusion limitation of ammonia nitrogen through the outer heterotrophic layers. In the first aerobic cell, depending on the availability of organic substrate, it appeared that the autotrophs were forced deeper into the biofilm due to the overgrown of heterotrophs over autotrophs resulting in ammonia flux limitation to the nitrifiers.

Although media were installed in the anoxic zones of IFAS 1, which were supplemented with direct feeding of 50% of the influent to prevent substrate limitation, total denitrification was not significantly different from the control and IFAS 2 systems where 100% of the influent was fed to the first anaerobic reactor, as shown in Table 5. From this data and data in Table 3, it is possible to see that all systems were under loaded with respect to oxidized nitrogen because there was no significant difference in total denitrification between the systems. In subsequent research, further studies will be conducted to evaluate the performance and feasibility of operating IFAS anoxic zones at lower SRTs and higher nitrate recycles to prevent the limitation of oxidized nitrogen. Denitrification in the aerobic zones was also determined from the mass balances around each reactor and it was found that there were no significant differences between the three systems. This is possibly because DO was maintained above 5.0 mg/l in the aerobic reactors. The amounts of denitrification observed in aerobic zones of the IFAS systems were 0.32 and 0.06 g N/day in IFAS 1 and IFAS 2, respectively. There was no measurable denitrification in the aerobic zone of the control system during this study.

Table 2 Average substances removal efficiencies for each biological treatment system

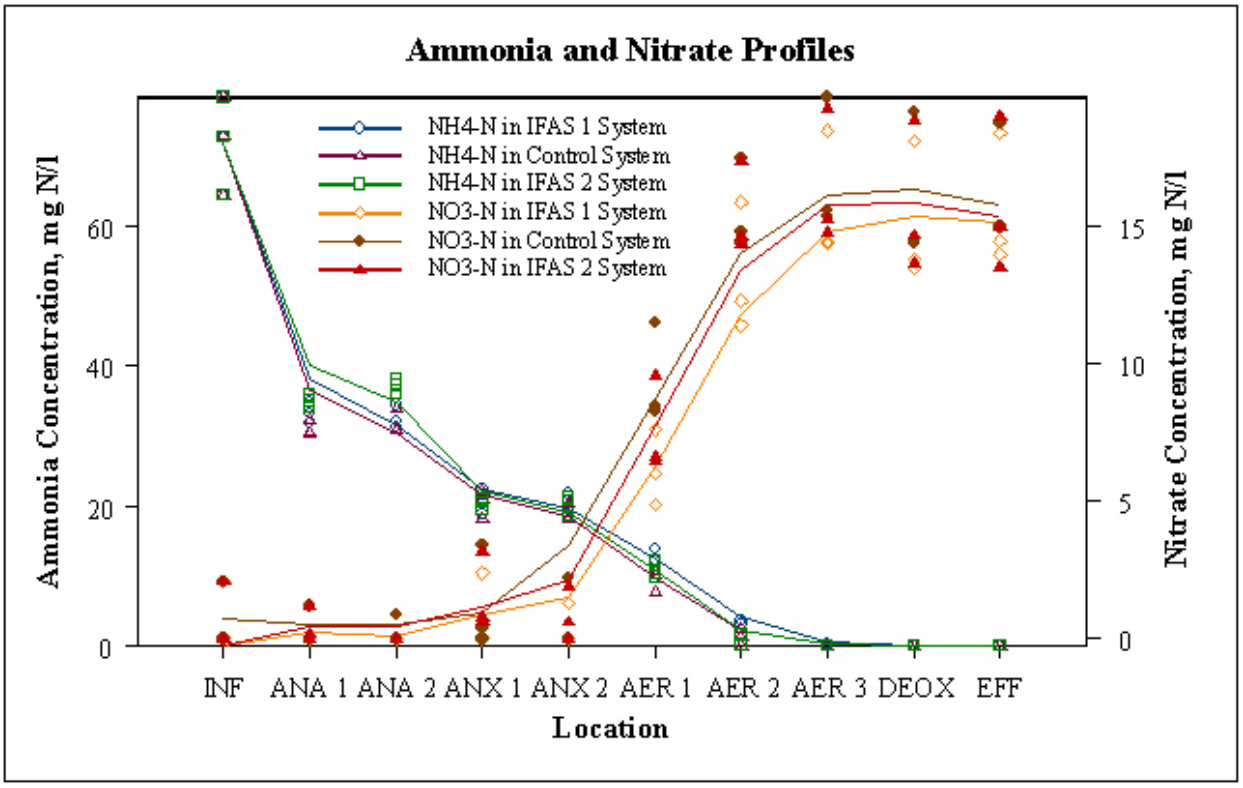
Parameters	**Mass Substances Applied (g/day)**			**Substances Removal (%)**		
	IFAS 1	**IFAS 2**	**Control**	**IFAS 1**	**IFAS 2**	**Control**
Organic Matter (COD)	103.19	105.88	104.82	95.10	95.15	94.81
Total Nitrogen	12.36	12.49	12.48	74.98	75.11	75.16
Phosphorus	5.78	5.91	5.86	61.04	70.27	71.33

Table 3 Average steady state concentrations and standard deviations of substances

Location	SCOD						NH4-N					
	IFAS 1		Control		IFAS 2		IFAS 1		Control		IFAS 2	
	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D
INF	604.50	39.95	604.50	39.95	604.50	39.95	71.87	7.05	71.87	7.05	71.87	7.05
ANA 1	113.21	15.08	103.83	18.90	158.97	19.64	33.24	1.47	31.08	1.11	34.96	0.90
ANA 2	90.51	13.19	79.20	24.31	139.93	15.43	32.61	1.69	31.84	1.81	37.05	1.11
ANX 1	40.98	11.55	33.37	8.71	33.42	5.84	20.93	1.83	20.40	1.98	20.35	0.83
ANX 2	39.05	12.65	33.41	14.66	29.60	10.09	20.30	1.26	19.57	1.29	20.13	1.44
AER 1	27.65	5.91	29.66	8.22	23.79	4.67	12.70	0.93	9.48	1.54	10.78	1.23
AER 2	27.65	5.91	29.66	8.22	25.71	5.72	3.26	0.36	1.21	1.25	1.02	0.88
AER 3	29.57	8.09	31.48	11.19	29.54	11.95	0.10	0.18	0.00	0.00	0.00	0.00
DEOX	27.52	5.82	27.65	5.91	25.71	5.72	0.00	0.00	0.00	0.00	0.00	0.00
EFF	29.57	8.09	31.48	11.19	29.54	11.95	0.00	0.00	0.00	0.00	0.00	0.00
Location	**NO3-N**						**PO4-P**					
	IFAS 1		Control		IFAS 2		IFAS 1		Control		IFAS 2	
	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D
INF	0.53	1.05	0.53	1.05	0.53	1.05	33.83	2.82	33.83	2.82	33.83	2.82
ANA 1	0.00	0.00	0.30	0.60	0.35	0.58	70.30	4.43	74.93	7.97	61.28	2.49
ANA 2	0.00	0.00	0.23	0.45	0.00	0.00	86.65	7.59	95.38	11.28	78.00	1.70
ANX 1	0.77	1.13	1.18	1.52	1.38	1.22	53.49	2.15	51.75	1.67	51.58	2.19
ANX 2	0.33	0.65	0.78	1.04	0.85	0.79	58.73	2.03	53.85	3.27	51.45	2.96
AER 1	6.29	1.15	9.02	1.68	7.16	1.65	38.43	2.14	33.28	3.17	41.60	10.80
AER 2	12.60	2.28	15.53	1.38	15.19	1.48	25.03	1.90	18.98	1.42	18.68	1.83
AER 3	15.52	1.99	16.65	2.04	16.03	2.20	13.18	2.12	9.70	1.42	10.13	2.04
DEOX	14.32	2.65	15.16	2.85	15.47	2.33	10.43	2.10	7.00	1.85	7.05	0.91
EFF	15.37	2.04	16.08	1.83	15.61	2.36	12.88	1.46	9.98	1.47	10.15	3.03

Table 4 Nitrification and nitrification rates in each aerobic cell for each system

Ammonia oxidation and nitrification rates in the aerobic cells (Spiked influent TKN)						
Location	**Nitrification, g/day**			**Nitrification Rate, mg/l/hr**		
	IFAS 1	**IFAS 2**	**Control**	**IFAS 1**	**IFAS 2**	**Control**
Aerobic Cell 1	3.69	6.61	6.22	7.67	12.40	11.68
Aerobic Cell 2	5.71	5.73	4.86	11.87	10.76	9.12
Aerobic Cell 3	3.39	3.58	3.31	6.36	6.71	6.21
Total ammonia oxidation	12.79	15.92	14.39			
Average ammonia oxidation and nitrification rates in the aerobic cells (Normal influent TKN)						
Location	**Nitrification, g/day**			**Nitrification Rate, mg/l/hr.**		
	IFAS 1	**IFAS 2**	**Control**	**IFAS 1**	**IFAS 2**	**Control**
Aerobic Cell 1	4.57	5.68	6.30	9.49	10.67	11.83
Aerobic Cell 2	5.67	5.67	5.16	11.79	13.40	9.69
Aerobic Cell 3	1.90	0.62	0.76	3.56	1.39	1.44
Total ammonia oxidation	12.14	11.97	12.23			



*Influent concentration is TKN

Figure 2. Ammonium and nitrate profiles in IFAS and conventional BNR systems

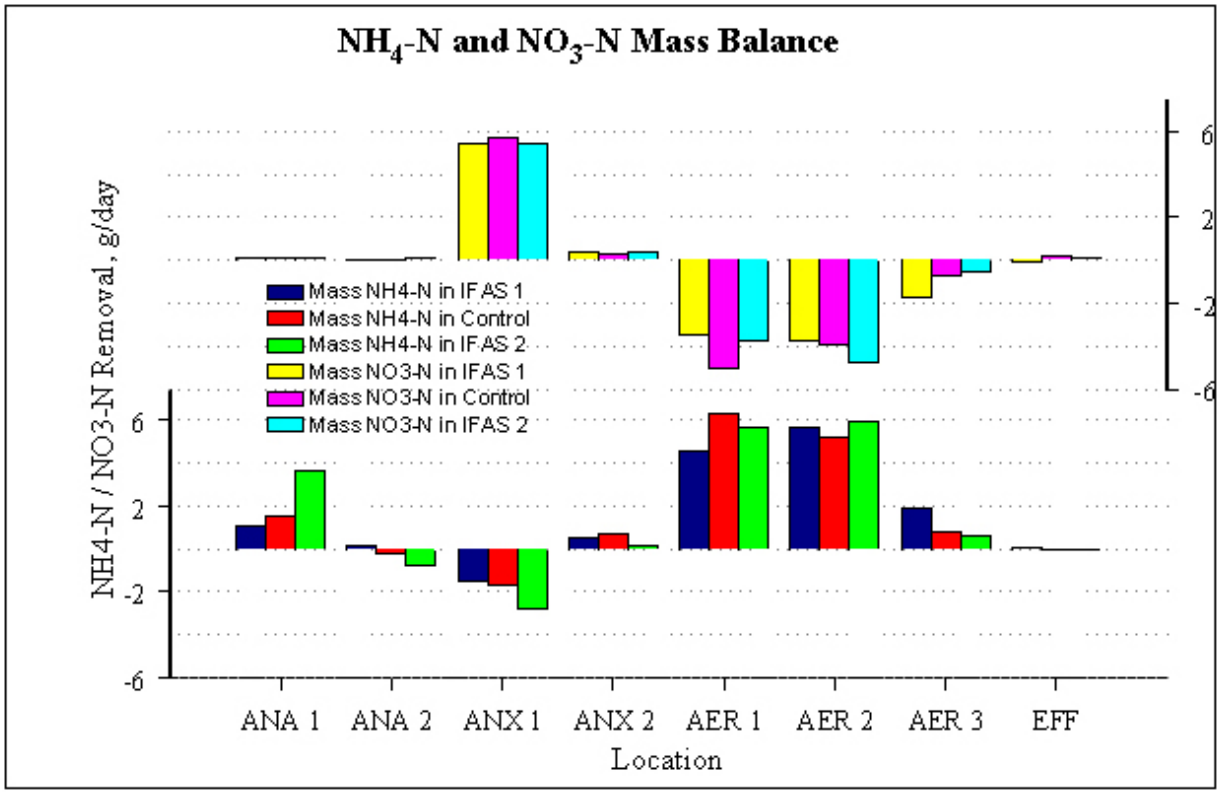
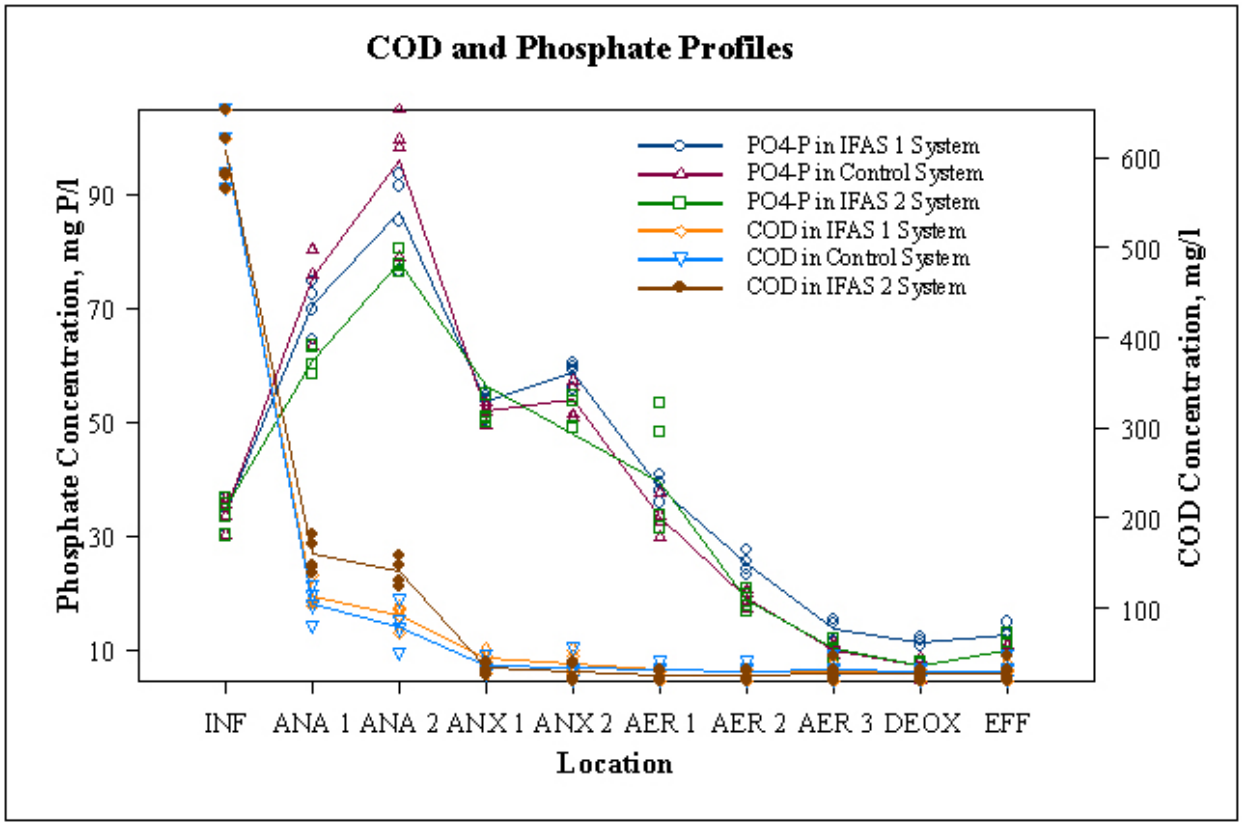


Figure 3. Ammonia and nitrate mass balances in IFAS and conventional BNR systems

Table 5 Total denitrification and denitrification rates in the IFAS and conventional BNR systems

Location	Denitrification, g/day			Denitrification Rate, mg/l/hr		
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control
Anoxic Cells 1	5.41	5.43	5.75	29.64	29.78	31.50
Anoxic Cells 2	0.36	0.42	0.34	1.95	2.30	1.84
Total denitrification	5.76	5.85	6.08			



*Influent concentrations are total phosphorus and total COD

Figure 4. Phosphate and COD profiles in IFAS and conventional BNR systems

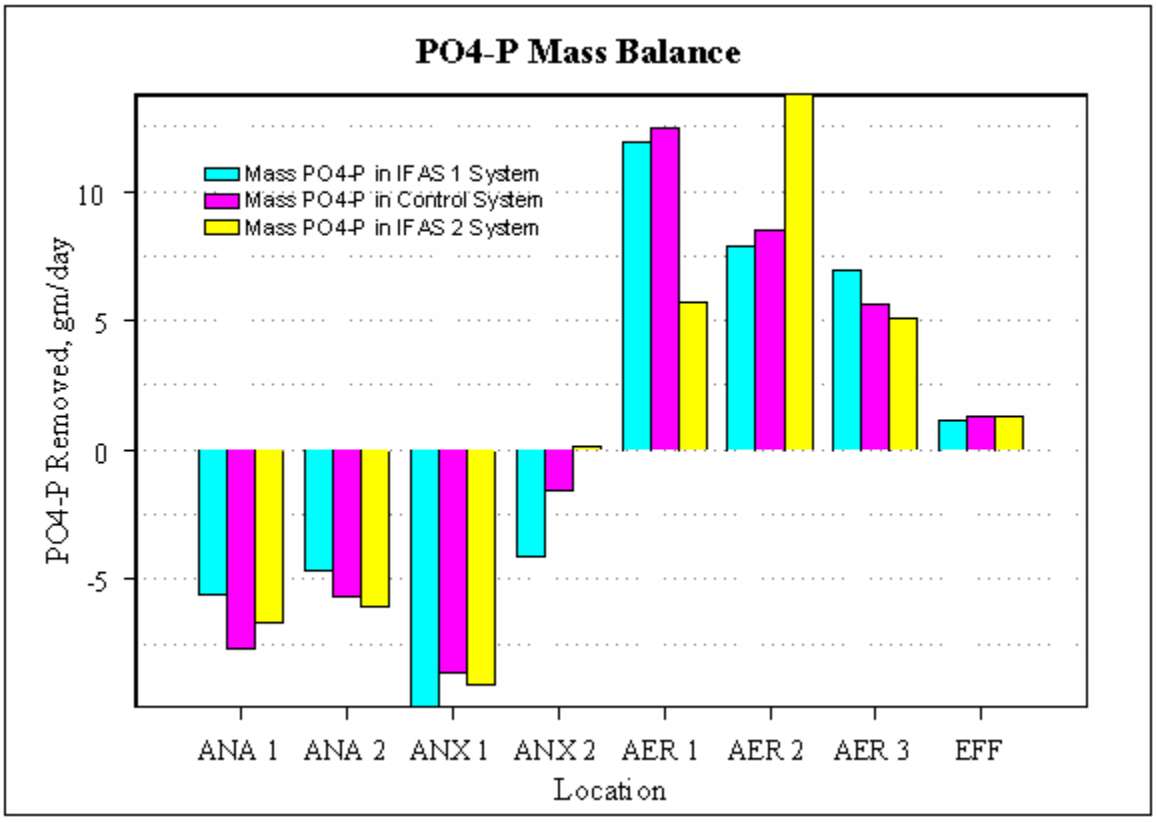


Figure 5. Mass phosphorus released and taken up in IFAS and conventional BNR systems

It was expected that the effluent phosphorus concentrations would be high in this study because of COD limitation, resulting from the low COD/TP ratio selected for the experimental design. The results are illustrated by Figure 4. Phosphorus mass balances were calculated around each reactor to evaluate phosphorus removal in the systems as shown in Figure 5. Table 6 represents the averages of 4 observations of phosphorus release and uptake in the systems. The same pH was maintained in all the systems so that phosphorus release and uptake could be accurately compared. The rates of phosphorus release and uptake in IFAS 1 and the control systems were slightly higher than the IFAS 2 system, resulting from adding substrate to the first anoxic tank thereby causing more phosphorus release and higher polyhydroxyalkanoate (PHA) accumulation in the control system. Unavailability of external substrates in anoxic zones resulted in higher net PHA utilization with nitrate as the electron acceptor in the IFAS 2 system, as shown in Figure 4. The split influent flow plus the integration of fixed film media in the anoxic tanks appeared to be a factor of reducing the EBPR performance on the IFAS 1 system as compared to the control and IFAS 2 systems. From the data in Table 7, it was calculated that 17 percent of the phosphorus

was released in the second anoxic tank of the IFAS 1 system compared to the 6.66 percent in that reactor of the control system. It is possible that biomass attached to the media or trapped inside the media racks released phosphorus when external substrate was available. The attached/trapped biomass with accumulated PHA would not subsequently experience aerobic conditions for the uptake of released phosphorus, and this would result in higher effluent phosphorus concentrations. These findings also suggest that integrating fixed film media into aerobic tanks to enhance nitrification and denitrification would have no negative effects on EBPR operated at 10 day MCRT and 10 ^{o}C. The EBPR performance may possibly be reduced due to integrating fixed film media in the anoxic reactors and splitting an influent flow to those tanks.

Tables 8 and 9 list the amounts of biomass growth on the media webs in the IFAS systems. The biomass attached to the media web in the first anoxic reactor of IFAS 1 was only 7.18 VSS g/ft^2, which was equivalent to 280 mg MLVSS/L. The location of media web in the aerobic zones provided different quantities of attached growth on the media. Higher amounts of biomass attached to the media web located in the first aerobic reactor of the IFAS 1 system because more biodegradable organic substrate was available.

Table 6 Phosphorus release, uptake and removal in the IFAS and conventional BNR systems

Observations	Phosphorus Release, g/day			Phosphorus Uptake, g/day		
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control
Observation 1	23.07	23.65	23.19	25.92	27.04	26.50
Observation 2	25.82	22.54	23.63	29.22	27.34	27.97
Observation 3	24.40	22.96	24.77	28.34	26.97	28.75
Observation 4	24.59	21.73	25.15	28.30	25.79	29.73
Average	24.47	22.72	24.18	27.95	26.79	28.24
	Total Uptake/Total P Release			P Removed, g/day		
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control
Observation 1	1.124	1.143	1.143	17.600	19.300	19.600
Observation 2	1.132	1.213	1.184	20.500	27.700	25.700
Observation 3	1.161	1.175	1.161	24.100	24.100	24.600
Observation 4	1.151	1.187	1.182	21.600	23.600	25.500
Average	1.142	1.179	1.167	20.950	23.675	23.850

Table 7 Phosphorus mass and percent release and uptake at different locations in the systems

Location	Mass Phosphorus Uptake/Release*			% Release			% Uptake		
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control
ANA 1	-5.58	-6.67	-7.67	22.92	30.57	32.27			
ANA 2	-4.69	-6.07	-5.71	19.25	27.86	24.02			
ANX 1	-9.94	-9.10	-8.63	40.84	41.72	36.32			
ANX 2	-4.14	0.10	-1.58	16.99		6.66		0.39	
AER 1	11.89	5.73	12.44				42.75	22.07	44.72
AER 2	7.87	13.73	8.52				28.30	52.88	30.63
AER 3	6.92	5.09	5.60				24.89	19.61	20.12
CLA	0.03	-0.07	-0.18		0.30	0.74	0.09		
DEOX	1.10	1.31	1.26				3.97	5.05	4.52
Release (-ve)	-24.34	-21.80	-23.76						
Uptake (+ve)	27.82	25.97	27.81						
Ratio (+ve/-ve)**	1.14	1.19	1.17						
Ratio (+ve/-ve)***	-2.71	-2.04	-2.08						

* Mass in unit of g/day

** Phosphorus uptake / total phosphorus release in anaerobic and anoxic reactors ratio

*** Phosphorus uptake / total phosphorus release in anaerobic reactors ratio

Table 8 Quantity of attached biomass on Accuweb at different locations

Reactor	TSS, g/ft^2			VSS, g/ft^2		
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control
Anoxic 1	10.09	-	-	7.18	-	-
Aerobic 1	25.01	-	-	19.08	-	-
Aerobic 2	17.48	23.03	-	14.38	18.40	-
Aerobic 3	-	23.42	-	-	17.87	-

Table 9 Quantity of MLVSS and equivalent MLVSS of attached biomass in the systems

Reactor	MLVSS Equivalent, mg/l			MLVSS, mg/l			Biomass on web (%)	
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2
Anoxic 1	279.87	-	-	3232.5	3430.0	3630.0	7.97	0.00
Aerobic 1	1203.38	-	-	3132.5	3715.0	3320.0	27.75	0.00
Aerobic 2	906.98	1740.54	-	3132.5	3715.0	3320.0	22.45	31.90
Aerobic 3	-	1690.54	-	3132.5	3715.0	3320.0	0.00	31.27

Previous studies with IFAS systems using integrated Ringlace® media were conducted at 5.3 day MCRT and 18 ^{o}C (Mitta, 1995). The review of experimental results indicated that, when operated at relatively high temperature, there was no difference in performance between the IFAS and control systems in terms of nitrification. All systems could achieve complete nitrification because of the high growth rate of the nitrifiers at the high temperature used, although the total suspended MCRT was maintained as low as 5.3 days. Since the systems were operated at low MCRT and this resulted in soluble biodegradable organic matter in solution in the aerobic zones of the systems, significant denitrification in the aerobic zones were observed in the fixed film media systems, but not in the control system. The denitrification in the aerobic zones in the IFAS systems resulted in higher total denitrification than the control system. Apparently because of the low MCRT, EBPR was not observed in this study.

CONCLUSIONS

Two IFAS and one conventional BNR pilot-scale VIP systems were operated in parallel at 10 day MCRT and 10 ^{o}C to evaluate the performance of IFAS wastewater treatment processes on biological nitrogen and phosphorus nutrient removal. One IFAS system had Accuweb® media integrated into the anoxic zones, and 50% of the influent feed was fed to the first anoxic reactor

to enhance denitrification. The first two-thirds of the aerobic zone in the system also had Accuweb media added to enhance nitrification. The second IFAS system had 100 percent of the influent fed to the first anaerobic tank, no media in the anoxic reactors, but Accuweb® media in the second two-thirds of the aerobic zone. The results from these systems were compared with the results from the conventional BNR control system, as well as with each other. The followings conclusions were drawn from the results obtained during this investigation.

1. All three systems accomplished complete nitrification at the relatively high mixed liquor suspended solids (MLSS) MCRT used (10 days), even though the experimental temperature was 10 ^{o}C, and the MLSS aerobic MCRTs were only 6.7 days for the control, 6.5 for IFAS 1, and 5.9 for IFAS 2.
2. There was no significant difference in denitrification performance between the control and the IFAS 2 system, which had fixed film media integrated into the anoxic zone, when 50% of the influent flow was added directly to the first anoxic reactors of the two systems. This was probably because the MCRT was relatively high and anoxic reactor nitrate loading was too limited to distinguish the performances between systems. It is likely that greater total denitrification could have been accomplished by the IFAS system if more nitrate had been recycled to the anoxic zones.
3. Very little denitrification occurred in the aerobic zones of the fixed film and control systems. Apparently, this was because the systems were operated with relative high dissolved oxygen concentrations in the aerobic zones.
4. The IFAS system with fixed film media only in the aerobic zone accomplished the same amount of enhanced biological phosphorus removal as the control system. However, the IFAS system with media integrated into the anoxic zone and with 50% of the influent flow diverted to the first anoxic reactor performed EBPR less efficiently. The experimental results from the IFAS 1 system compared to the control and IFAS 2 systems indicated that high phosphorus release occurred in the second anoxic zone because of the addition of substrate to that zone. Consequently, the IFAS 1 system could not take up phosphorus as efficiently in the aerobic zones to concentrations as low as the control system. It appears that some of the attached microorganisms released phosphorus in the media containing anoxic zone that could not subsequently taken up in the aerobic zone.

5. The amounts of biomass on the fixed film media varied with the location of media in the aerobic zones. The highest biomass attachment (19.08 g VSS/ft^2) was observed in the first aerobic reactor, probably because of higher heterotrophic attachment. By contrast, only 7.18 g VSS/ft^2 was observed in the first anoxic tank.

The results of this study combined with the results obtained by Mitta (1995) indicate that IFAS systems do not obtain improved nitrification compared to conventional three-state BNR systems at either relatively high MCRT or moderate temperature. However, it was demonstrated that IFAS systems can perform EBPR at high MCRT, and can accomplish greater denitrification at moderate temperature.

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CHAPTER 4: THE EFFECTS OF ANOXIC MEDIA ON DENITRIFICATION IN IFAS BNR WASTEWATER TREATMENT SYSTEMS

T. SRIWIRIYARAT AND C.W. RANDALL*

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University, 418 Durham Hall, Blacksburg, VA 24061, USA

Abstract—

The application of Integrated Fixed Film Activated Sludge (IFAS) processes for wastewater treatment has become popular worldwide because IFAS can provide a robust method for overcoming organic overloading, and for enhancing both nitrification and denitrification in the aerobic zones of activated sludge plants, with minimal or no expansion of existing tankage. Most IFAS nutrient removal studies have investigated the addition of fixed-film media into only the aerobic zone, and have not investigated placement of the media into the anoxic zone. Also, the systems investigated typically were not designed to include enhanced biological phosphorus removal (EBPR), because they were mostly conducted at low operating mean cell residence times (MCRTs) and low temperatures to learn the benefits of IFAS under limiting conditions for conventional activated sludge. Consequently, EBPR 'washed-out' of the systems at the MCRT-temperature combinations used. This investigation, however, was designed to determine the advantages and disadvantages of integrating fixed film media into the anoxic zone of biological nutrient removal (BNR) systems designed and operated to include EBPR. Three UCT configuration BNR systems were used for the investigation, two with Accuweb® IFAS media, and a control system without. Initially both IFAS systems had media in their aerobic zones, and one had media in the anoxic zone, but in subsequent experiments both had anoxic media and only one had aerobic media. The ability of the web-like Accuweb® media to enhance nitrogen removal when integrated into the anoxic and aerobic zones was evaluated at two COD/TP ratios and two operating MCRTs. The results under the conditions in this study showed that the integration of media has the potential to substantially enhance nitrogen removal when biodegradable organic substrate (COD) is not limiting, but will provide no significant nutrient removal benefit when the systems are underloaded. The IFAS systems had higher specific denitrification rates when compared to the control, and the IFAS systems accomplished a higher

fraction of aerobic zone denitrification than the control. Surprisingly, media in the anoxic zone substantially increased denitrification in the aerobic zone of a system that contained no media in the aerobic zone. However, because of the underloaded conditions of the three systems during the experimental phases, there was no significant difference in the total amount of nitrogen removal accomplished by the IFAS systems when compared to the Control system. EBPR was maintained in all systems throughout the investigation until the influent phosphorus concentration was decreased during Phase III to increase the influent COD/TP ratio from 20 to 52. This resulted in failure of EBPR in both of the IFAS systems, and in the Control.

Key words—Activated Sludge, IFAS, Accuweb, Denitrification, EBPR, MCRT, COD/TP ratio.

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*Author to whom all correspondence should be addressed:

[Tel: 540-231-6018, Fax: 540-231-7916, E-mail: cliff@vt.edu]

INTRODUCTION

The integration of fixed film media into activated sludge reactors has been found to be useful for modifying organically overloaded systems and for the enhancement of nitrification and denitrification in systems otherwise too small for complete nitrification under low temperature conditions (Lessel, 1991; Lessel, 1993; Sen, 1995; Sen and Randall, 1994). Known as Integrated Fixed Film Activated Sludge (IFAS) or hybrid processes, they most commonly are applied to enhance nitrification and denitrification by placing the media into the aerobic basins of overloaded wastewater treatment plants located in the temperate zones. Biofilms are established on the support media under aerobic conditions to supplement nitrifier growth and to retain nitrifiers in the biological system when they would otherwise 'wash-out', so that year round nitrification can be accomplished without increasing the mixed liquor suspended solids (MLSS) mean cell retention time (MCRT) or expanding the aerobic reactor volume. In addition, it has been observed that IFAS systems typically accomplish considerable denitrification in the aerobic zone and, therefore, produce lower total effluent nitrogen concentrations than would a conventional biological nutrient removal (BNR) system operated under the same conditions (Sen, 1995).

When operated at low MCRT, biodegradable organic substrates (COD) frequently breakthrough the anaerobic and anoxic zones of BNR systems and enter the aerobic zones at higher concentrations than usually desired because of the tendency for this to stimulate filamentous growth. However, in IFAS systems, the higher COD concentrations could result in increased substrate diffusion into the biofilm, reaching depths at which nitrate becomes the most effective electron acceptor, thereby resulting in enhanced denitrification by the media biofilms in aerobic zones. However, the enhanced denitrification observations reported in the literature were observed in systems that were not accomplishing enhanced biological phosphorus removal (EBPR), i.e., in systems where competition for substrate between EBPR microorganisms and denitrifiers did not take place. It seems likely that with the inclusion of EBPR, substrate would be more limited for denitrification, in both the anoxic and aerobic zones, and this would reduce the potential for denitrification in aerobic zones.

Also, there have been very few investigations of the performance of fixed film media integrated into the anoxic zones of BNR systems. The potential of this application to enhance COD removal and denitrification was investigated in The Netherlands by Hao et al. (1995) in anoxic reactors preceding an oxidation ditch, using fibrous carriers as the fixed-film media. Two systems were operated in parallel to compare the denitrification capacities when one contained the fibrous carrier media and the other did not. Both systems were supplemented with excess organic substrates. A third system without any fibrous carriers installed and without supplemented substrates was also operated to evaluate endogenous denitrification rates. As the nitrate loading increased over 20 g NOx-N/(kg VSS/day), the denitrification rate in the system with the fibrous carriers and unlimited external substrate increased continuously with no upper limit during studies whereas the system without supplemental carbon reached the limit of 0.7 mg N/(g VSS/h) and the system without carriers but supplemented with excess carbon reached the limit of 1.4 mg N/(g VSS/h). In another study in the Netherlands, the fibrous carriers were integrated into the anoxic tank of a system receiving domestic wastewaters at low temperatures (10-15 ^{o}C). In this study, the system accomplished over 90% denitrification efficiency when the loading rate of the oxidized nitrogen was less than 0.4 kg N/m3-d (Liu et al., 1996a). Additionally, the fibrous carriers were used in China in the anoxic zone of a combination fixed-

film activated sludge system, called the SBF-AF process, in which there was no return activated sludge (RAS) to the biofilm reactor. The system was operated at high temperature (20-30 ^{o}C), high HRT (16-22.9 hrs), and high MCRT (50 days). In the SBF-AF investigation, the denitrification rate decreased when the NOx-N loading rate was greater than 0.7 kg NOx-N/m^3/day (Liu et al., 1996b). However, no attempt was made to specifically evaluate the biofilm process in the anoxic tanks in the above studies, and either EBPR was not incorporated or EBPR was enhanced with chemical addition.

The objectives of this research were to investigate the potential for enhancing system denitrification by integrating biofilm support media into the anoxic zones of three stages biological nutrient removal (BNR) activated sludge systems, and to investigate the effects of substrate competition between EBPR and denitrification reactions on system performance.

MATERIALS AND METHODS

Process Setup

Two IFAS systems and one conventional UCT/VIP pilot-scale systems were operated at a temperature of 10 ^{o}C at Virginia Tech, Blacksburg USA to evaluate the potential benefits of integrating fixed film media into the anoxic zones to enhance denitrification and improve total nitrogen removal. Each system consisted of two anaerobic (7.6 L ea.), two anoxic (7.6 L ea.), and three aerobic cells (22.2 L ea.) in series, in the order given. The total volume of each system was approximately 100 liters, with a small variation depending upon the amount of media in each system. The hydraulic retention time (HRT) was maintained at approximately 13±1 hours with a flow rate of 175 L/day. These systems were fed with municipal sewage pumped and stored for 24 hours for temperature adjustment and fermentation, and then supplemented with sodium acetate, urea, and potassium dihydrogenphosphate to increase the wastewater strength and to maintain the desired COD/TP ratios. Experiments were conducted at two different COD/TP ratios (20 and 52) with the systems operated at a 6 day MCRT, and, during the Phase I experiments, operated at a low COD/TP ratio (18) and a 10 day MCRT with a 50-50 split of the influent flow to the first anaerobic and first anoxic reactors of the control and one of the IFAS systems. The flow to the second IFAS system was not split. The operating conditions during the

experiments of Phases I, II, and III are summarized in Table 1. The MCRTs were maintained by daily wasting the appropriate amount of volume from the third aerobic reactor.

During the preliminary Phase I experiments, as shown in Figure 1, 0.3 ft^2 of one inch-mesh Accuweb® media was installed into each of the first and second anoxic tanks of IFAS 1 and, additionally, 1.4 ft^2 of the same media was installed into each of the first two reactors of the IFAS 1 aerobic zone. The other IFAS system (IFAS 2) had 2.1 ft^2 of Accuweb® media integrated into the last two reactors of its aerobic zone, and none in the anoxic zone. Another UCT/VIP system was operated without any media installed and served as the control system. The influent flow was split 50-50 between the first anaerobic and first anoxic reactors of IFAS 1 and the Control system to evaluate the effects of directing organic substrate directly to the anoxic zones to enhance denitrification. The mixed liquor nitrate recycle (NR) rate was set at 150%, the return activated sludge (RAS) rate at 100%, for a total recycle of 250%, and the mixed liquor recycle from the last anoxic reactor to the first anaerobic reactor (MLR) at 100% of the influent flow rate (Q). The systems were operated at 10 days MCRT and a COD/TP ratio of 18 during the preliminary study period. The excess biomass was wasted from the last aerobic reactors with the flow rate of 7.6, 8.0, and 7.4 L/day from IFAS 1, Control, and IFAS 2 systems, respectively. The strength of the sewage was approximately 600 mg/L COD, 70 mg /L nitrogen, and 34 mg /L of phosphate phosphorus throughout Phase I.

After the first phase of operation, each IFAS system was modified as illustrated by Figure 2. Three-tenths of a square foot of 1 inch-type Accuweb® media was installed into each of the first and second anoxic tanks of both IFAS systems and only the middle aerobic reactor of IFAS 2 had media installed (3 ft^2). The control UCT/VIP system without any media installed was operated throughout the study. The systems were operated at 6 day total MCRTs (4.7 days aerobic MCRTs) and the other operating parameters were the same as during Phase I. All three systems were operated at two COD/TP ratios, 20 and 52, to evaluate the effects of the COD/TP ratio on denitrification stimulated by integrated fixed film media. Split influent flow was eliminated, and 100% of the influent flow entered the first anaerobic reactor of all three systems. Also, the NR and RAS were increased to 200% of the influent flow, a total recycle of 400%, for this phase of the experiments. The excess sludge was pumped out from the last aerobic reactor

of IFAS 1, Control, and IFAS 2 systems about 12, 13, and 12 L/day, respectively. The results from these experiments were used to investigate changes in system and nutrient removal performance from placement of integrated media into both the anoxic and the aerobic reactors.

Table 1 Summary of operating conditions during the experimental phases

Operating Parameters	IFAS 1			Units
	Phase I	Phase II	Phase III	
Influent to 1st anaerobic	50	100	100	% Influent Flow
Influent to 1st anoxic	50	0	0	% Influent Flow
	Control			
	Phase I	Phase II	Phase III	
Influent to 1st anaerobic	50	100	100	% Influent Flow
Influent to 1st anoxic	50	0	0	% Influent Flow
	IFAS 2			
	Phase I	Phase II	Phase III	
Influent to 1st anaerobic	100	100	100	% Influent Flow
Influent to 1st anoxic	0	0	0	% Influent Flow
Total MCRT, all systems	10	6	6	Days
Recycle Rates, all systems	NR 1.5Q, RAS 1Q MLR 1Q	NR 2Q, RAS 2Q, MLR 1Q	NR 2Q, RAS 2Q, MLR 1Q	Influent Flow (Q)
Influent Characteristics, all systems	Phase I	Phase II	Phase III	
Total COD	604.5 ±40	675 ±66	589 ±21	mg COD/L
Total Nitrogen	72 ±6.2	103 ±7.4	112 ±4.2	mg N/L
Total Phosphorus	34 ±2.8	33.5 ±0.8	11.1 ±0.8	mg P/L
COD/TP	18 ±2.6	20.2 ±2.3	52 ±3.9	
COD/TKN	8.6 ±0.9	6.6 ±0.6	5.2 ±0.2	

Mixed liquor suspended solid (MLSS), mixed liquor volatile suspended solid (MLVSS), chemical oxygen demand (COD), anions (nitrite, nitrate, phosphate, and sulfate), and cations (ammonia-N, potassium, magnesium, and calcium) were monitored until the systems reached steady state conditions. At steady state, influent and effluent Total Kjeldahl Nitrogen (TKN) and Total Phosphorus (TP) were also measured. MLSS, MLVSS, TKN, TP and COD were analyzed in accordance with Standard Methods for the Examination of Water and Wastewater, 19th Edition, (APHA, 1995). Anions were analyzed by a Dionex 2010I ion chromatography (IC) with an IONPAC AS4A-SC column and electrochemical conductivity detector (Dionex Corp.,Sunnyvale, CA). Cations were analyzed by Dionex 120 ion chromatography (Dionex Corp.,Sunnyvale, CA).

Growth on the media was measured at steady state by scrubbing biofilm from media web removed from the anoxic and aerobic reactors by using a syringe which was made specifically designed to provide a high water pressure spray. The biofilm suspended solids in the collected water were separated by centrifuging for 10 minutes and draining the supernatant. The biomass samples were dried in the oven at 105 ^{o}C for at least 24 hours. The dried biomass samples were weighed to determine the biomass dry weight. After that, the samples were ignited at 550 ^{o}C for 20 minutes in accordance with Standard Methods (APHA, 1995). The percentage of volatile solids was calculated and then used to determine the total volatile solids on the media webs.

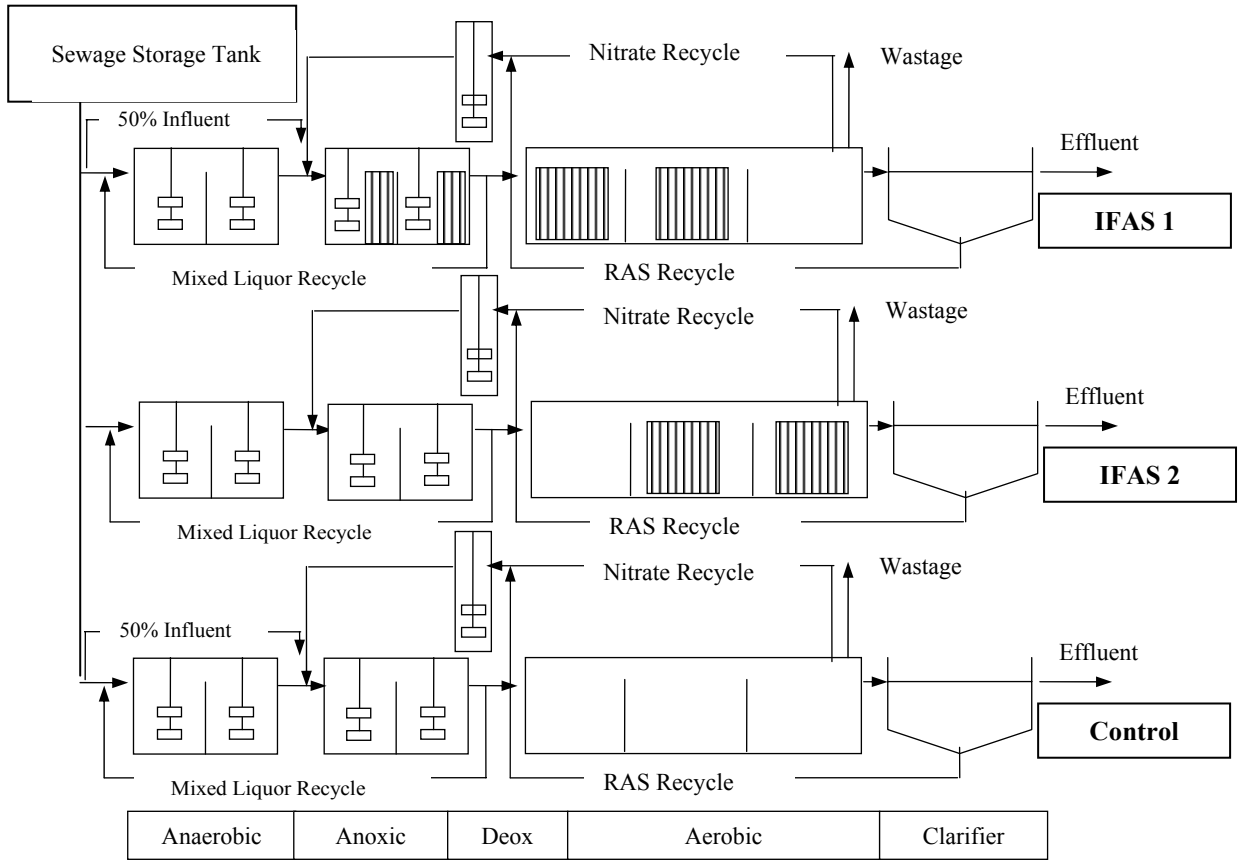


Figure 1. Schematic diagrams of the three systems during the preliminary phase (Phase I)

Denitrification rate evaluations

Denitrification rates for the systems at steady state were determined from the results of both continuous flow system performance and batch tests. It was possible to use performance data to determine the denitrification rates in the continuous flow systems because each zone had more than one reactor. Therefore, the first reactor of each zone was typically overloaded, and

maximum rates of reaction were measurable. The biofilm denitrification rates were determined by removing biofilm media racks from the anoxic reactors of a specific system and submerging them in batch reactors filled with acetic acid-and-nitrate spiked effluent from the same system. The decline in oxidized nitrogen concentrations was used to determine the denitrification rates that could be attributed to the fixed films on the media webs. The liquid phase was kept stirred all the time during the batch test studies. The COD, CH_3COOH, nitrite, nitrate and phosphate concentrations were monitored for 6 hours for rate determinations.

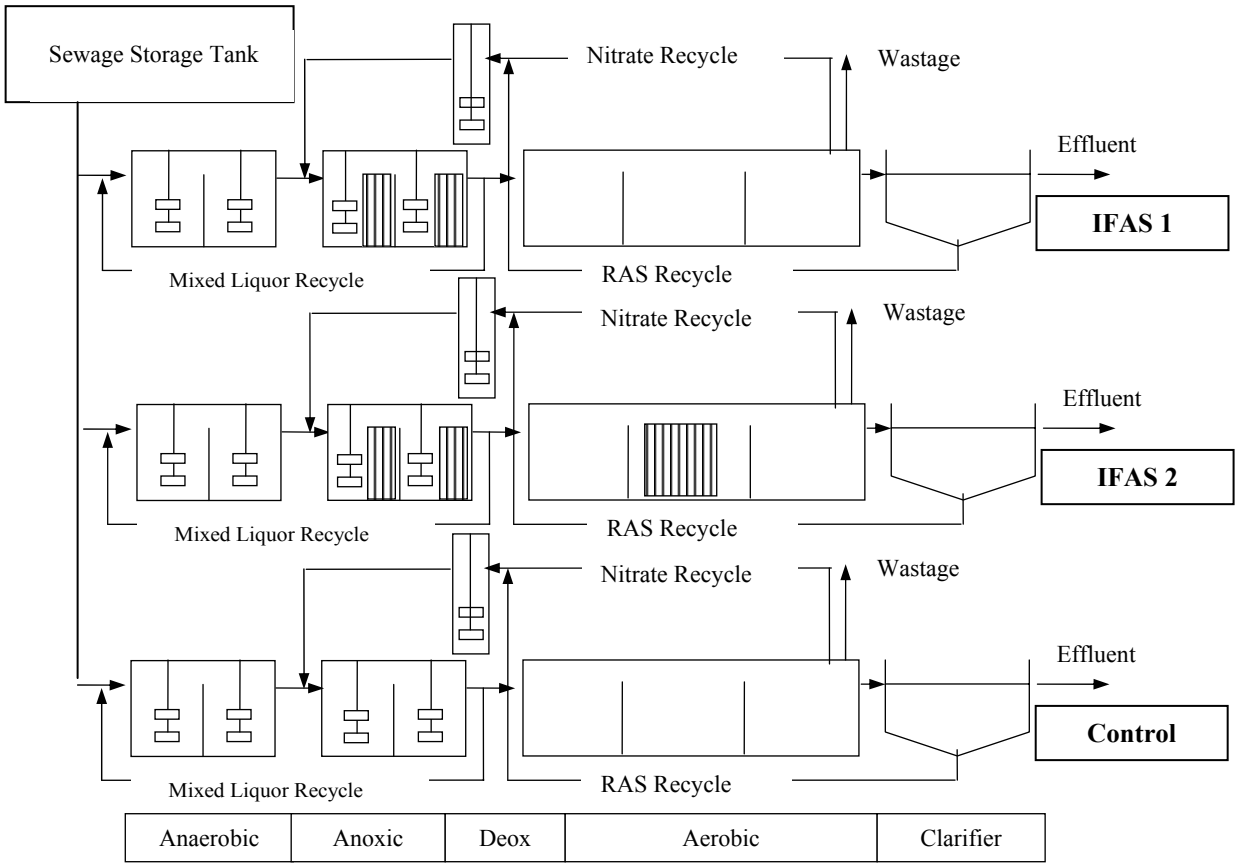


Figure 2. Schematic diagram for IFAS studies during experiment (Phase II and III)

RESULTS AND DISCUSSION

The installation of fixed film media into some of the reactors resulted in significant shifts of the biomass distribution in the IFAS BNR systems relative to the Control system, and also affected the total amount of biomass maintained in each of the systems. The resulting total biomass concentrations in each of the reactors, expressed as MLVSS and including the fixed film biomass, are shown in Table 2 and compared to the MLVSS concentrations in the Control

system reactors. The results show how the fixed film media concentrated biomass into the reactors containing the media, and decreased the MLVSS concentrations in the other reactors. The results indicate that installation of fixed film media into the anoxic reactors decreased the total biomass maintained in the systems and the amount of waste biomass produced, while the utilization of media in one or more aerobic reactors increased the total biomass in the systems and the amounts of waste sludge relative to the Control or to the IFAS system without aerobic media. It also is clear that utilization of media in any of the reactors reduced the amount of biomass maintained in the anaerobic zone, thereby decreasing the anaerobic mass fraction of the activated sludge, with potential impacts on EBPR effectiveness.

Comparison of the biomass amounts in the anoxic reactors of IFAS 1 during Phase II with the Control is particularly instructive. Placing fixed film media into the anoxic reactors decreased the amount of biomass maintained and wasted from the three stage BNR system by 8.5%, but the amounts of biomass in the IFAS 1 anoxic reactors was nearly identical to the amounts in the Control anoxic reactors, implying that the denitrification potentials of the two systems should be similar. The fixed film biomass in the anoxic reactors, as expected, reduced the biomass amounts in the other reactors. The amount of biomass in the anaerobic zone was nearly 14% less than in the Control anaerobic zone, and the amount in the IFAS 1 aerobic zone was reduced by 8.2%. One would expect both of these decreases to reduce the EBPR and nitrification potentials of the IFAS 1 system. Examination of the IFAS 2, Phase II results show that media in the aerobic 2 reactor in addition to in the anoxic reactors had an insignificant effect upon the total biomass in the BNR system, but reduced the amount of biomass in the anoxic zone by 22.2% compared to IFAS 1. It would be expected that this would reduce the denitrification potential of the IFAS 2 anoxic zone.

COD and Nutrient Removals

The average removal efficiencies for COD, phosphorus and nitrogen accomplished by the IFAS and Control systems during Phases I, II, and III are illustrated in the three graphs of Figure 3. The average substrate concentrations and standard deviations are shown in Table 3, 4, and 5. COD removal was approximately 95 percent for all three systems and all operating conditions throughout the three experimental phases, resulting in effluent concentrations of approximately

30 mg/L. It appears that COD removal was independent of the operating conditions and only non-biodegradable soluble substrates, which could not be degraded any further, were left in the effluents. The Phase I and II experiments demonstrated that EBPR could be maintained in IFAS systems, but indicated that EBPR is less robust than in conventional three stage BNR systems. The EBPR removal efficiencies during Phase I were 70% (10.2 mg P/L effluent) in the Control (split influent flow) and IFAS 2 (100% influent to anaerobic zone) systems, but only 60% (13.6 mg P/L effluent) in IFAS 1 (split influent flow). These results indicate that EBPR was more efficient per unit biodegradable COD in the Control system than in either of the two IFAS systems.

Table 2 Changes in biomass distributions with installation of fixed film media

System	Total Biomass, MLVSS + Fixed Film, expressed as MLVSS, mg/L							System Total, g
	Ana. 1	Ana. 2	Anoxic 1	Anoxic 2	Aerobic 1	Aerobic 2	Aerobic 3	
	PHASE I							
IFAS 1	(2298)	2298	**3496**	**3496**	**4336**	**4040**	3133	**321.8**
IFAS 2	(1983)	1983	(3430)	3430	(3525)	**5471**	**4463**	**343.6**
Control	(2503)	2503	(3630)	3630	(3527)	(3424)	3320	**320.2**
	PHASE II							
IFAS 1	(1558)	1558	**3230**	**3200**	(2865)	(2671)	2478	**246.3**
IFAS 2	(1400)	1400	**2510**	**2495**	(2448)	**4169**	2353	**249.4**
Control	(1808)	1808	(3203)	3203	(3056)	(2910)	2763	**269.1**
	PHASE III							
IFAS 1	(973)	973	**2083**	**2097**	(1997)	(1896)	1796	**170.5**
IFAS 2	(1114)	1114	**2122**	**2148**	(2054)	**3157**	1866	**199.4**
Control	(1276)	1276	(2312)	2312	(2314)	(2316)	2318	**208.0**

( ) estimated values **Values in bold include fixed film biomass**

Table 3 Average steady state concentrations and standard deviations of substances Phase I

Location	SCOD						NH4-N					
	IFAS 1		Control		IFAS 2		IFAS 1		Control		IFAS 2	
	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D
INF	604.50	39.95	604.50	39.95	604.50	39.95	71.87	7.05	71.87	7.05	71.87	7.05
ANA 1	113.21	15.08	103.83	18.90	158.97	19.64	33.24	1.47	31.08	1.11	34.96	0.90
ANA 2	90.51	13.19	79.20	24.31	139.93	15.43	32.61	1.69	31.84	1.81	37.05	1.11
ANX 1	40.98	11.55	33.37	8.71	33.42	5.84	20.93	1.83	20.40	1.98	20.35	0.83
ANX 2	39.05	12.65	33.41	14.66	29.60	10.09	20.30	1.26	19.57	1.29	20.13	1.44
AER 1	27.65	5.91	29.66	8.22	23.79	4.67	12.70	0.93	9.48	1.54	10.78	1.23
AER 2	27.65	5.91	29.66	8.22	25.71	5.72	3.26	0.36	1.21	1.25	1.02	0.88
AER 3	29.57	8.09	31.48	11.19	29.54	11.95	0.10	0.18	0.00	0.00	0.00	0.00
DEOX	27.52	5.82	27.65	5.91	25.71	5.72	0.00	0.00	0.00	0.00	0.00	0.00
EFF	29.57	8.09	31.48	11.19	29.54	11.95	0.00	0.00	0.00	0.00	0.00	0.00
Location	**NO3-N**						**PO4-P**					
	IFAS 1		**Control**		**IFAS 2**		**IFAS 1**		**Control**		**IFAS 2**	
	Avg.	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**
INF	0.53	1.05	0.53	1.05	0.53	1.05	33.83	2.82	33.83	2.82	33.83	2.82
ANA 1	0.00	0.00	0.30	0.60	0.35	0.58	70.30	4.43	74.93	7.97	61.28	2.49
ANA 2	0.00	0.00	0.23	0.45	0.00	0.00	86.65	7.59	95.38	11.28	78.00	1.70
ANX 1	0.77	1.13	1.18	1.52	1.38	1.22	53.49	2.15	51.75	1.67	51.58	2.19
ANX 2	0.33	0.65	0.78	1.04	0.85	0.79	58.73	2.03	53.85	3.27	51.45	2.96
AER 1	6.29	1.15	9.02	1.68	7.16	1.65	38.43	2.14	33.28	3.17	41.60	10.80
AER 2	12.60	2.28	15.53	1.38	15.19	1.48	25.03	1.90	18.98	1.42	18.68	1.83
AER 3	15.52	1.99	16.65	2.04	16.03	2.20	13.18	2.12	9.70	1.42	10.13	2.04
DEOX	14.32	2.65	15.16	2.85	15.47	2.33	10.43	2.10	7.00	1.85	7.05	0.91
EFF	15.37	2.04	16.08	1.83	15.61	2.36	12.88	1.46	9.98	1.47	10.15	3.03

Phosphorus removal efficiency in the Control and IFAS 2 systems decreased by nearly 10 percent from Phase I performances during Phase II when 100% of the influent entered the anaerobic zone but the MCRT was decreased from 10 days to 6 days. Apparently the effect of changing the MCRT had a bigger impact on EBPR in the Control system than increasing the biodegradable organics to the anaerobic zone. Curiously, the drop in % phosphorus removal was the same in IFAS 2 as in the Control, indicating that the MCRT had a lesser effect on the IFAS system, because there was no offsetting increase in the biodegradable organics to IFAS 2. Apparently the competing effects on EBPR of MCRT decrease and additional biodegradable organics to the anaerobic zone exactly compensated each other in the IFAS 1 system because the phosphorus removal was the same during Phase II as was observed during Phase I. During Phase III, however, phosphorus removal decreased by 50 percent or more in all three systems

when the influent phosphorus was decreased from 33.5 to 11.1 mg/L, even though the measurable amounts of phosphorus in the effluents exceeded 7.5 mg P/L. The intent of decreasing the influent phosphorus was to increase the COD/TP from 20 to 52 so that less substrate would be used for EBPR and more would be available for the dentrifiers, but the change had a substantially greater effect on EBPR performance than expected.

Table 4 Average steady state concentrations and standard deviations of substances Phase II

Phase II

Location	SCOD						NH4-N					
	IFAS 1		Control		IFAS 2		IFAS 1		Control		IFAS 2	
	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D
INF	675.08	66.05	675.08	66.05	675.08	66.05	102.90	7.36	102.90	7.36	102.90	7.36
ANA 1	116.07	14.71	91.60	15.42	92.58	10.77	48.00	2.62	45.85	0.72	46.99	4.27
ANA 2	93.29	23.70	79.51	8.28	72.19	10.97	48.66	2.52	47.56	0.93	46.79	3.21
ANX 1	46.26	22.28	36.50	11.52	34.89	4.75	25.73	2.64	23.29	2.17	25.84	6.28
ANX 2	33.27	6.65	33.27	6.65	34.89	4.75	24.33	2.34	22.90	1.81	24.12	5.30
AER 1	33.27	6.65	33.27	6.65	34.89	4.75	18.24	1.93	15.23	1.86	16.84	4.13
AER 2	33.27	6.65	33.27	6.65	34.89	4.75	11.81	2.48	6.78	1.01	8.01	2.95
AER 3	33.27	6.65	33.27	6.65	34.89	4.75	5.64	1.84	1.94	0.67	2.43	0.68
DEOX	34.89	4.75	33.27	6.65	34.89	4.75	4.45	2.15	0.91	0.84	1.14	0.34
EFF	33.27	6.65	33.27	6.65	34.89	4.75	4.69	2.45	0.55	0.40	1.34	0.92
Location	**NO3-N**						**PO4-P**					
	IFAS 1		Control		IFAS 2		IFAS 1		Control		IFAS 2	
	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D
INF	0.20	0.23	0.20	0.23	0.20	0.23	33.54	0.79	33.54	0.79	33.54	0.79
ANA 1	0.88	1.11	0.45	0.37	0.55	0.36	42.86	3.22	48.64	3.36	48.27	7.25
ANA 2	0.35	0.30	0.40	0.23	0.52	0.34	56.64	6.26	66.72	5.60	62.56	5.16
ANX 1	10.37	1.77	15.12	3.61	13.19	4.61	32.47	4.12	33.24	3.43	37.70	10.59
ANX 2	9.29	2.13	13.03	3.55	12.51	4.72	31.94	3.62	33.36	3.37	37.17	10.61
AER 1	15.36	0.76	20.08	4.05	20.13	3.20	24.35	4.05	24.36	1.38	26.47	5.58
AER 2	21.39	0.93	27.70	3.24	28.21	2.00	16.94	1.73	18.50	1.04	19.24	3.29
AER 3	26.73	1.31	31.98	2.49	33.02	2.47	13.08	2.25	12.65	1.56	12.70	2.08
DEOX	26.28	2.15	31.84	2.31	33.40	2.04	12.44	2.37	11.31	1.60	10.65	2.52
EFF	25.80	1.96	31.78	2.54	32.75	1.85	13.21	3.06	11.92	1.29	12.28	3.08

The total system nitrogen removal efficiencies were approximately 75 % (17.5 mg N/L effluent) for all three systems when they were operated at 10 days MCRT regardless of influent flow split and IFAS media installation. The total nitrogen removal decreased in all three systems when the MCRT was decreased to 6 days, i.e. to about 68% in IFAS 1, 66% in the Control, and 67% in IFAS 2. Nitrogen removals improved slightly when the systems were operated at the much

higher COD/TP ratio of phase III, but less than expected. The nitrate profiles and average nitrate mass balances around each reactor are shown in Figure 4 to confirm the nitrate reactions in the systems. Most differences in nitrate profiles and mass balances, particularly those observed during Phase III, were because of differences in nitrification in the systems, which resulted in different nitrogen loadings to the anoxic reactors. Nitrification was more complete in the Control.

Table 5 Average steady state concentrations and standard deviations of substances Phase III

Phase III

Location	SCOD						NH4-N					
	IFAS 1		Control		IFAS 2		IFAS 1		Control		IFAS 2	
	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D	Avg.	S.D
INF	588.65	20.64	588.65	20.64	588.65	20.64	111.72	4.25	111.72	4.25	111.72	4.25
ANA 1	163.36	15.32	129.45	19.45	168.16	17.14	62.84	4.69	52.23	5.83	62.40	3.67
ANA 2	160.92	14.77	124.31	23.08	160.90	19.39	62.88	4.01	55.15	7.57	63.24	4.71
ANX 1	37.60	16.39	25.62	5.25	34.97	9.52	34.24	3.02	23.78	3.80	38.08	3.24
ANX 2	30.32	11.76	34.15	9.40	23.11	4.79	33.24	3.08	21.98	3.54	35.55	3.69
AER 1	30.20	7.03	28.04	8.32	23.11	4.79	26.18	3.05	14.59	3.54	30.84	3.34
AER 2	25.44	5.06	30.48	11.68	27.91	4.58	21.87	5.15	2.84	3.78	23.92	3.55
AER 3	27.82	4.40	25.69	11.07	25.49	5.06	17.30	5.59	0.00	0.00	19.59	4.81
DEOX	32.62	6.51	23.20	8.01	27.87	8.03	15.81	6.10	0.00	0.00	16.10	4.52
EFF	30.20	7.03	26.91	6.72	37.47	14.96	15.68	5.65	0.00	0.00	17.97	3.86
Location	**NO3-N**						**PO4-P**					
	IFAS 1		**Control**		**IFAS 2**		**IFAS 1**		**Control**		**IFAS 2**	
	Avg.	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**	**Avg.**	**S.D**
INF	0.68	0.46	0.68	0.46	0.68	0.46	11.12	0.78	11.12	0.78	11.12	0.78
ANA 1	0.49	0.52	0.43	0.59	0.66	0.45	10.56	0.78	10.69	0.78	10.16	0.46
ANA 2	0.57	0.56	0.30	0.44	0.68	0.48	11.20	0.61	12.15	1.11	12.15	1.00
ANX 1	4.05	2.29	11.02	1.20	3.66	1.87	9.58	0.45	10.05	0.38	9.84	0.78
ANX 2	2.91	2.33	9.29	3.03	2.90	2.58	9.58	0.45	9.56	0.35	9.96	0.71
AER 1	5.93	2.81	17.16	2.29	5.75	2.48	7.95	1.01	8.92	0.51	9.27	0.56
AER 2	10.68	4.18	22.28	2.68	8.59	3.26	8.73	0.35	7.81	0.71	7.98	0.87
AER 3	14.93	4.41	27.23	3.13	13.74	3.40	8.43	0.50	7.71	0.45	7.88	0.23
DEOX	14.97	4.53	26.95	3.06	13.94	3.46	8.31	0.40	7.38	0.52	7.59	1.14
EFF	15.21	4.39	27.54	2.95	13.73	3.10	8.40	0.39	7.71	0.80	8.11	0.64

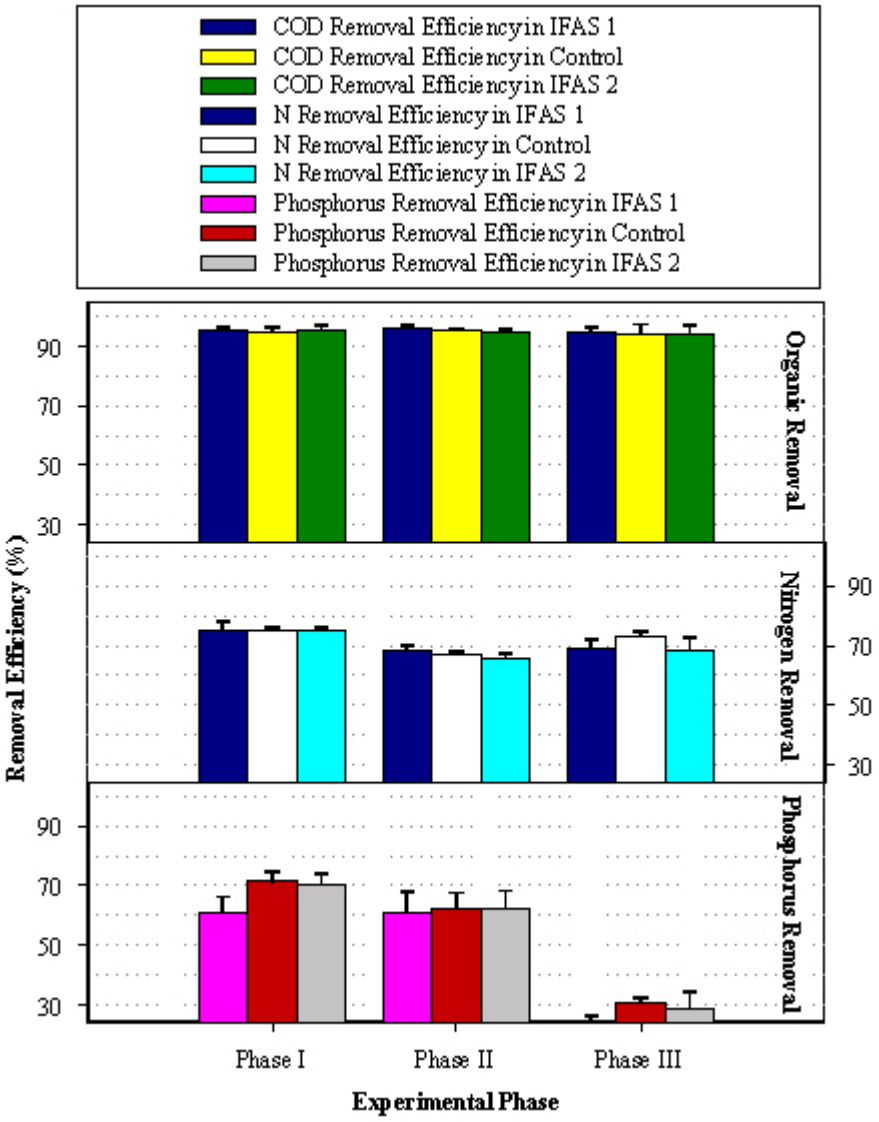


Figure 3: The average COD, nitrogen, and phosphorus removal efficiencies during Phases I, II and III

Denitrification with step-feed influent flow

During the preliminary (Phase I) studies, the systems were maintained at the COD/TP ratio of 18, which represents a low COD/TP ratio condition, i.e., COD limiting conditions, in order to maintain phosphorus in the effluents to enable evaluation of EBPR kinetic rates. Also, it was assumed that operating the systems under COD limiting conditions would result in domination of PAO organisms in the systems, with the removal of large amounts of bioavailable organics in the anaerobic reactor. This would reduce the amounts of COD available for denitrification. To

investigate the significance of the increased competition for substrate between EBPR and denitrification, the IFAS 1 and Control systems were operated with the influent flow split 50-50 between the first anaerobic and first anoxic reactors, i.e. to supplement the organic substrate available for denitrification, while IFAS 2 was operated with 100 percent of the influent flow entering the first anaerobic reactor.

Table 6 Statistical evaluation of denitrification in IFAS-Accuweb® and Control Systems

T-Test between IFAS 1 and Control for Total Denitrification in Phase I					
H_0: There is no difference in the mean total denitrification between the IFAS and Control systems					
H_A: There is a difference in the mean total denitrification between the IFAS and Control systems					
Alternative Hypothesis	T-Value	Prob Level	Decision -5%	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	-0.1058	0.9221	Accept Ho	0.050706	0.010164
Difference < 0	-0.1058	0.46105	Accept Ho	0.059512	0.012106
Difference > 0	-0.1058	0.53895	Accept Ho	0.041712	0.008208
Difference: (Pilot system=Control)-(Pilot system=IFAS1)					
T-Test between IFAS 2 and Control for Total Denitrification in Phase I					
Difference <> 0	0.1491	0.88869	Accept Ho	0.05158	0.010386
Difference < 0	0.1491	0.55566	Accept Ho	0.038242	0.007415
Difference > 0	0.1491	0.44434	Accept Ho	0.064421	0.01331
Difference: (Pilot system=Control)-(Pilot system=IFAS2)					

The results from the Phase I experiments are shown in Figures 3 & 4, and in Table 6. In Figure 4, nitrate removal is shown as positive and nitrate production as negative. The results indicate that the denitrification performances of the two IFAS systems and the control system were statistically the same at the significance level of 0.05, for the COD/TP ratio of 18, even though the influent flow was split between the anaerobic and anoxic zones of two of the systems. This result was contrary to expectations and indicated that some factor other than COD was limiting denitrification in all three systems. Note that Figure 4 shows there was negligible denitrification in the anaerobic zones of the three systems during Phase I.

The limitation of denitrification was investigated by determining the specific nitrate loading rates and specific denitrification rates. The rates were calculated and normalized by the volatile suspended solids (VSS) concentrations while including the attached biomass if the reactor had fixed film media installed. The average available COD/NO_3-N ratios incoming to the first anoxic reactors were calculated and found to be 10.72, 9.44, and 5.99 in IFAS 1, the Control, and IFAS 2, respectively, which indicated that, during Phase I, all three systems were underloaded with respect to oxidized nitrogen. In comparison, Stensel, in Randall et al. (1992), derived a COD/NO3-N ratio which was related to net biomass yield (Y_N) as the stoichiometric limit as shown in Equations 1 and 2.

$$\frac{COD}{N} = \frac{2.86}{1 - 1.134 Y_N} \quad (1)$$

$$Y_N = \frac{Y}{1 + b_H MCRT} \quad (2)$$

where b_H is endogenous decay coefficient, d^{-1}; Y is true yield coefficient, g VSS/g COD used. With the true yield and decay parameters of 0.31 mg VSS/mg COD used and 0.037 day^{-1} determined by Sen (1995) under anoxic conditions in the laboratory, the COD/NO_3-N ratios are calculated to be 4.04 and 3.85 at MCRTs of 6 days and 10 days, respectively. As a result of split influent flows to IFAS 1 and the Control, the COD/NO_3-N ratios to IFAS 1 and the Control were higher than to IFAS 2. Also, the ratio to the control system was slightly less than to the IFAS 1 system even though they were fed the same amounts of organic substrate, because more substrate uptake with phosphorus release for cellular substrate storage took place in the Control anaerobic zone. Therefore, the highest specific denitrification rates in the first anoxic reactors were 9.66, 10.42, and 9.48 mg N/g VSS/h in the IFAS 1, Control, and IFAS 2 systems, respectively. The results indicate that split flow did not enhance denitrification because nitrate was limiting, and that installing media in the anoxic zone decreased the denitrification rate by increasing the amount of biomass in the anoxic reactors. Regardless of the similar system nitrogen removal efficiencies, the data plotted in Figure 5 indicate that the installation of media into anoxic reactors has the potential to provide higher denitrification rates and greater nitrogen removal than anoxic reactors without media when the nitrate loading is not limiting under the studied conditions. There was a linear relationship between denitrification rate and nitrate loading for IFAS 1, which had anoxic media, indicating that its performance was limited by the nitrate

loading and possibly would have been higher had loadings been higher, whereas the rates in both the Control and IFAS 2 (no anoxic media) systems appeared to reach their highest potentials during the phase I experiments.

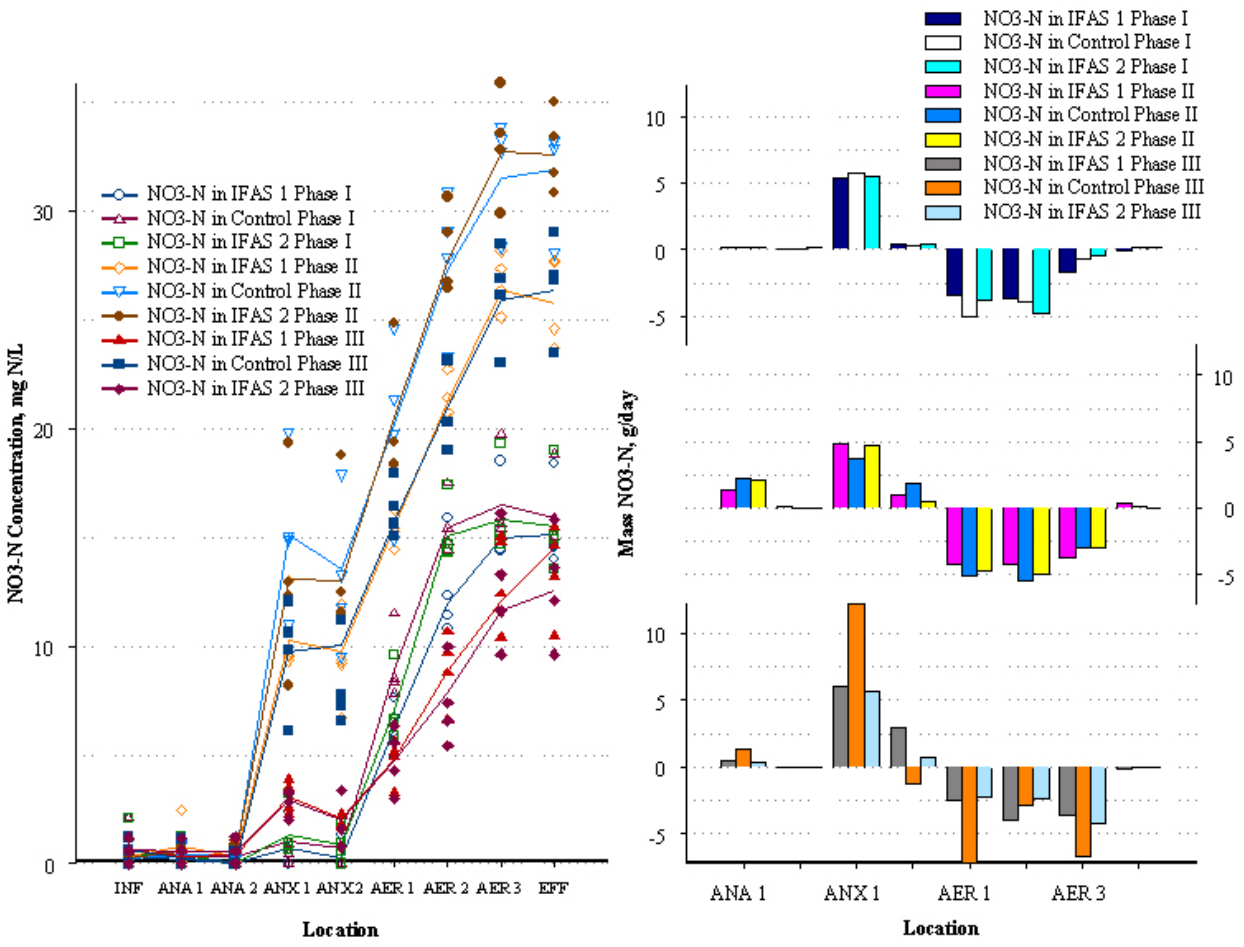


Figure 4: Nitrate profiles and nitrate mass balances around each reactor during Phases I, II, and III

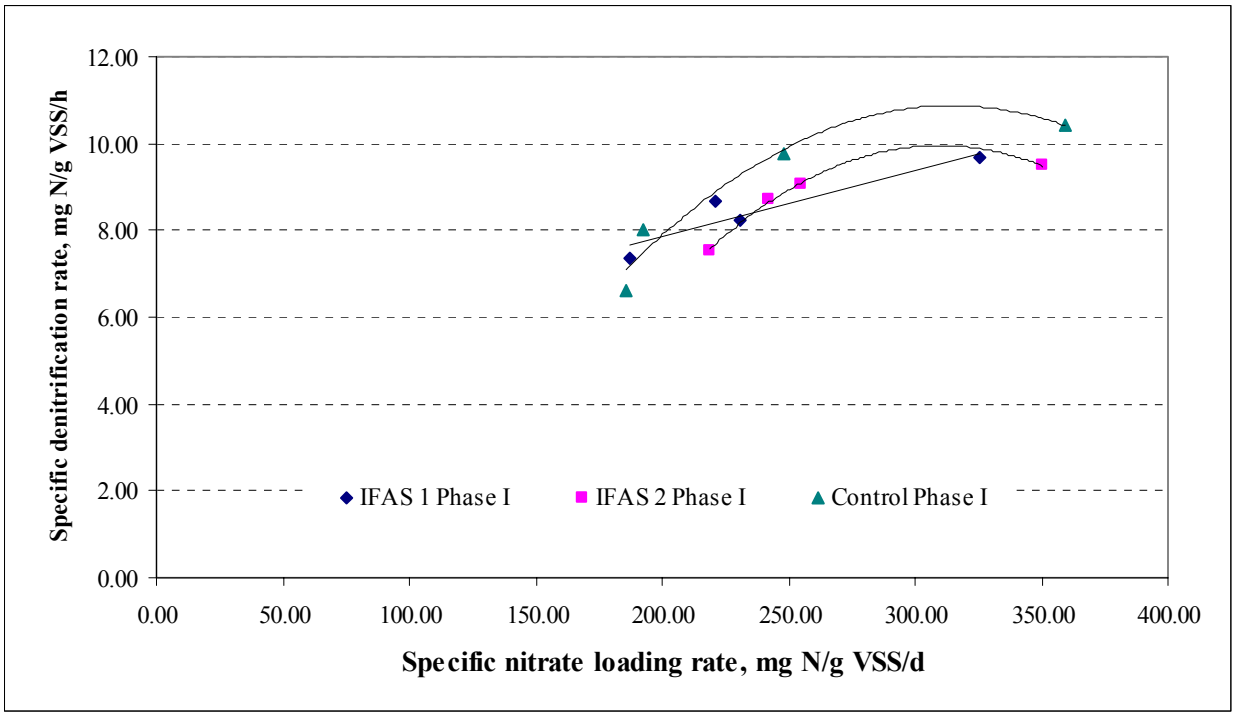


Figure 5: Relationship between specific denitrification rates and specific nitrate loading rates in the first anoxic cells during Phase I

Denitrification with COD/TP ratio

In the second phase of the experiments, the total MCRT was lowered to 6 days (4.7 Days aerobic MCRT) to decrease the amount of substrate removed in the anaerobic zone and thus increase the amount of soluble substrate entering the first anoxic zones, in an effort to enhance denitrification. Additionally, the NR and RAS recycle rates were increased to 200% in an effort to avoid nitrate loading limitation, at least in the first anoxic reactors. This discussion will be limited to denitrification in the first anoxic cells, where neither substrate nor nitrate was limiting. With a COD/TP of 20, the average specific biodegradable organic substrate loading rates entering the first anoxic zones were 1.06, 0.67, and 0.79 g COD/g VSS/day in IFAS 1, the Control, and IFAS 2, respectively, and the COD/NO_3-N ratios were 1.54, 0.95, and 0.91, respectively. All COD/NO_3-N ratios were less than the 4.04 stoichiometric ratio calculated using Stensel's equations (1992), indicating that all anoxic reactors were COD limited with respect to denitrification. This resulted in considerable nitrate recycling to the first anaerobic cells, and substantial amounts of denitrification in the first anaerobic reactors of all three systems

(Figure 4). The result was that a lot of the substrate was consumed in the anaerobic zones and less substrate entered the first anoxic cell. However, the data in Figure 4 also illustrates that nitrate was not limiting in the first anoxic reactors because significant amounts of denitrification occurred in the second anoxic reactors of all three systems. Therefore, the maximum denitrification rates were occurring in all three of the first anoxic reactors, and the two with the IFAS media installed had rates higher than the Control.

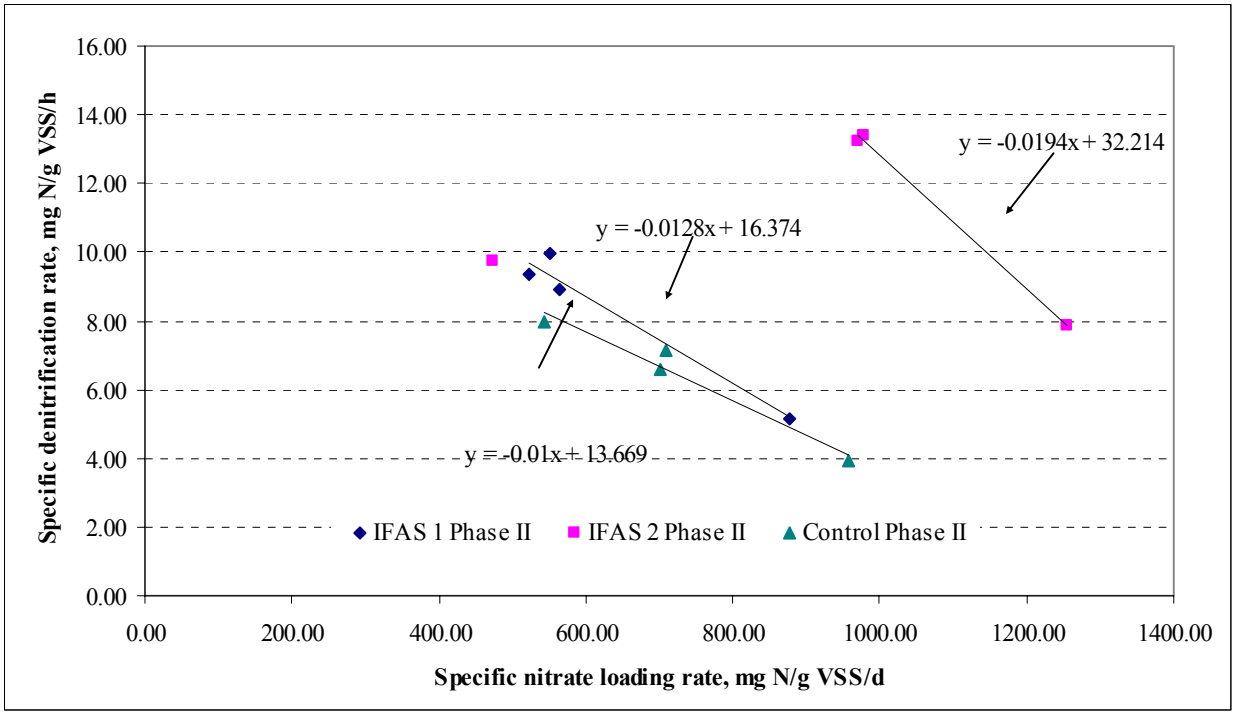


Figure 6: Relationship between specific denitrification rates and specific nitrate loading rates in the first anoxic cells of the systems during Phase II

Figure 6 indicates that during Phase II the systems were overloaded with respect to oxidized nitrogen because the specific denitrification rates decreased when nitrate loadings increased. The figure shows that the specific denitrification rates decreased in the first anoxic reactors of the Control, IFAS 1, and IFAS 2 when the specific nitrate loading was increased above 542, 551, and 979 mg N/g VSS/day, respectively. Interestingly, IFAS 2, with media in the middle aerobic reactor in addition to media in the anoxic reactor, had the highest VSS specific denitrification rates. This was because the VSS concentrations in IFAS 2 were lower, but indicated that the

denitrifier fraction was greater in the MLVSS. At the specific nitrate loading rate of 979.32 mg N/g VSS/day, the specific denitrification rate was 13.41 mg N/g VSS/h. The COD/NO_3-N ratio for IFAS 2 at the highest specific denitrification rate was 1.07. The highest specific denitrification rates in IFAS 1 and the Control were 9.97 and 8.00 mg N/g VSS/h corresponding to COD/NO_3-N ratios of 1.79 and 1.11, respectively.

For the Phase III experiments, the COD/TP ratio was increased to 52, mostly by reducing the influent phosphorus concentration, while the systems were maintained at the same 6 day operating MCRT. The expectation was that there would be an increase in the amounts of substrates entering the first anoxic zones, and the denitrification rates would increase. However, over the first 30 days after the phosphorus loading was decreased, the EBPR in all three systems gradually decreased and eventually disappeared. Ammonia nitrogen in both IFAS systems was only partially nitrified whereas ammonia nitrogen in the control system was completely oxidized. This caused higher nitrate loadings to the first anoxic reactor of the Control system compared to both IFAS systems. As a result of the higher oxidized nitrogen concentrations in the anoxic zone of the Control system, nitrates were recycled to the first anaerobic zone, and much of the substrates entering the anaerobic zone were used for denitrification, thereby reducing the amounts of biodegradable organic substrates that entered the first anoxic cell of the Control system, relative to the IFAS systems. After EBPR had ceased, the average COD/NO_3-N ratios entering the first anoxic cells were 5.66, 2.12, and 4.54 in IFAS 1, the Control, and IFAS 2 systems, respectively.

The nitrate loading rates to the Control system were higher than to the IFAS systems during Phase III, as illustrated by Figure 7, because nitrification was complete in the Control system. The COD/NO_3-N ratios in the IFAS systems were twice as much as the ratio in the Control system because of this. It is, therefore, most likely that the IFAS systems were underloaded with respect to oxidized nitrogen loadings and could have accomplished considerably more denitrification had the nitrates been available, resulting in much higher denitrification rates. However, IFAS 2 seemed to provide higher denitrification rate than the IFAS 1 and Control systems because the specific denitrification rate in IFAS 1 apparently reached the optimum rate and the COD/NO_3-N ratio in the Control system was over the stoichiometric limit. The specific

denitrification rate in the Control system would have been limited by COD if the specific nitrate loading rate had been increased. If it is assumed that the specific oxidized nitrogen loading rate were increased the same as the loading rate in the Control system (1115.87 mg N/g VSS/day), the specific denitrification rate would have increased to 31.51 mg N/g VSS/h. This would be possible because there was an excess of substrate entering the first anoxic reactor.

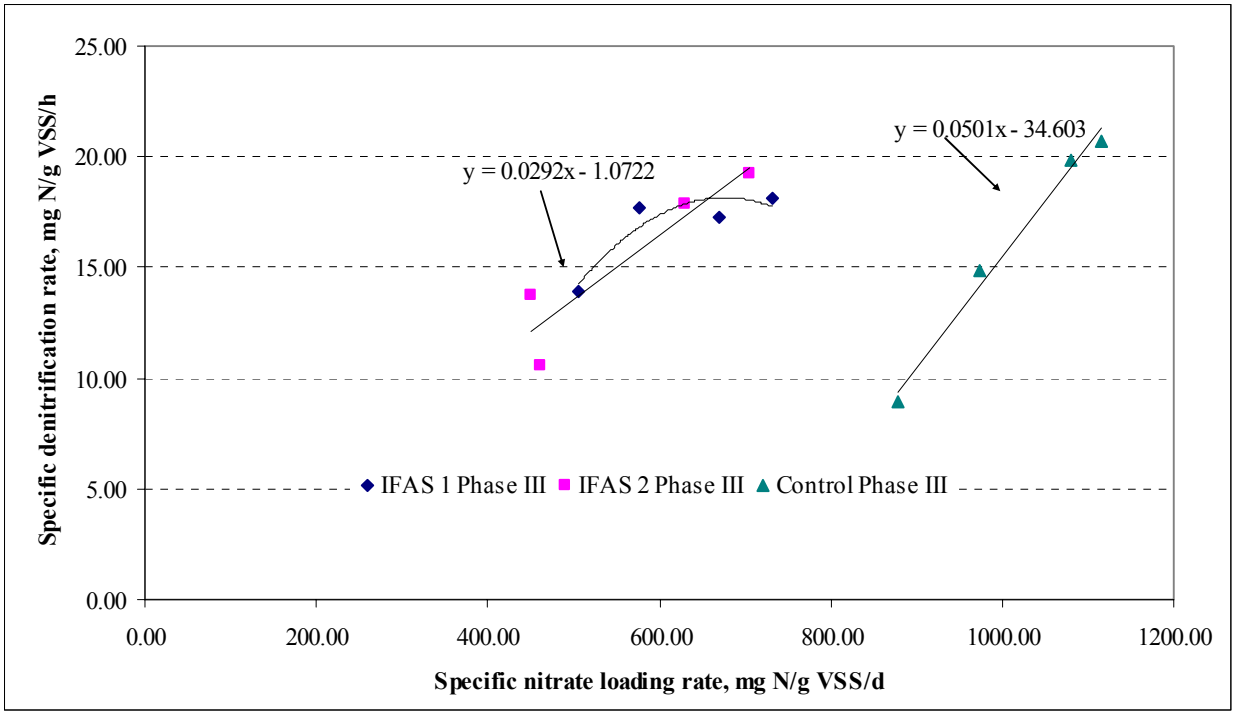


Figure 7: Relationship between specific denitrification rates and specific nitrate loading rates in the first anoxic cells of the systems during Phase III

Denitrification in the aerobic zones

Figure 8 and Table 8 shows the denitrification fractions of the total that took place in the different zones of the three systems during each phase of the experiments. The results show that high denitrification occurred in the anaerobic zones in all systems during the Phase II experiments because all systems were under substrate limiting conditions and more nitrates were recycled back from the last aerobic zones and final clarifiers than could be denitrified in the anoxic zones. The results also confirmed that denitrification was enhanced in the aerobic zones of the IFAS systems as reported in the literature (Sen and Randall, 1994). The data indicate there was no denitrification in the aerobic zone of the Control system in all phases of the

experiments, probably because the mixed liquor DO concentrations were high. Approximately 13.5 percent of the nitrates were denitrified in the aerobic zones of each of the IFAS systems even though IFAS 1 did not have fixed film media installed in the aerobic reactors but IFAS 2 did. A possible interpretation is that the anoxic fixed film media in IFAS 1 seeded the MLSS with denitrifiers that continued to function even in the aerobic zone. After the COD/TP was increased and EBPR ceased during Phase III, more substrate entered the aerobic zones and denitrification increased in the aerobic zones of the IFAS systems, but it was higher in IFAS 2 compared to IFAS 1 by an average of 7% and as much as 19% in one run.

Denitrification with attached biomass

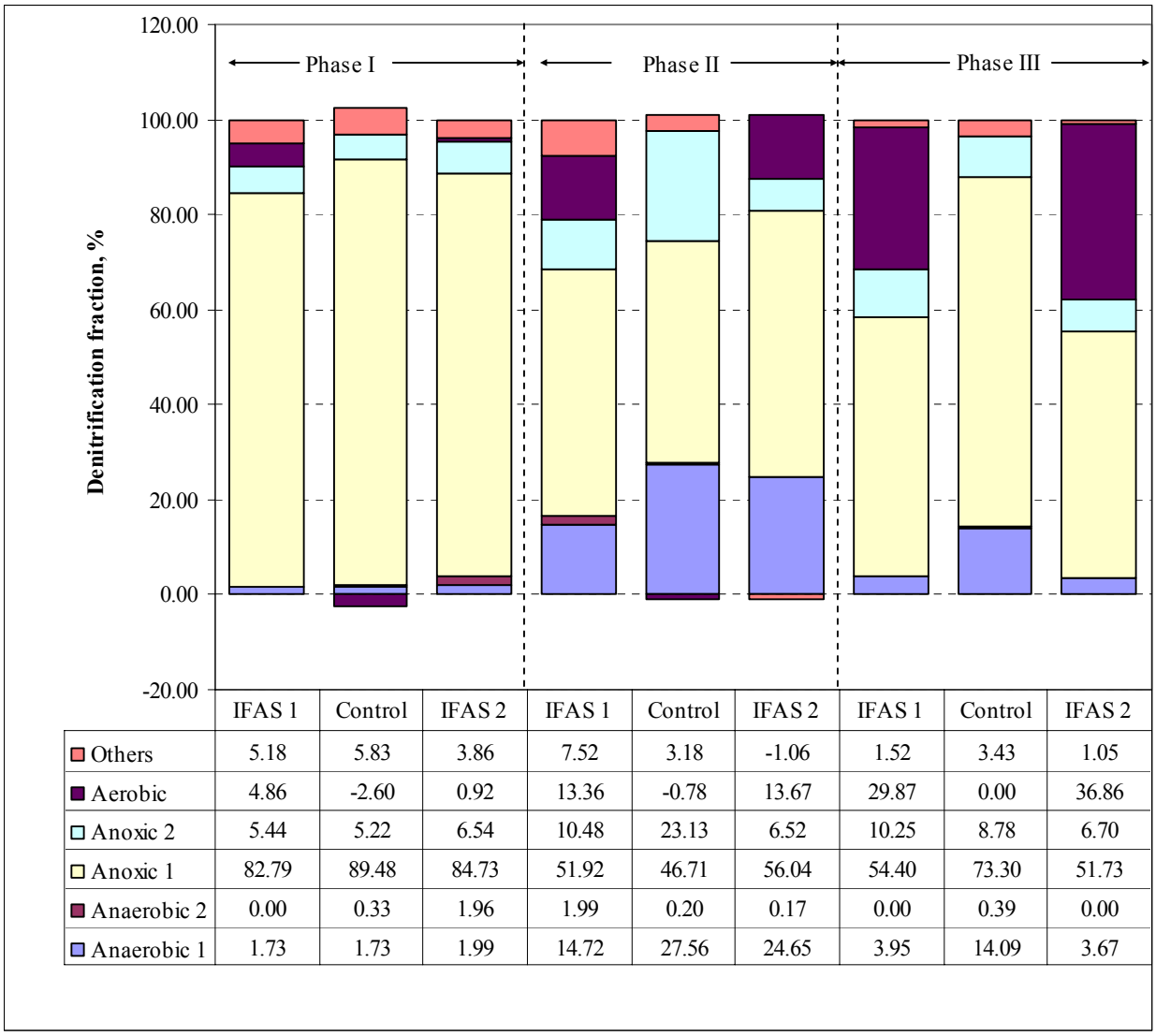
Table 7 shows the normalized maximum specific denitrification rates by biomass attached on Accuweb® media observed during this investigation. The rates were determined during batch tests with excess substrates. The average rates during Phase III were lower than during Phase II, especially in the second anoxic reactors, apparently because of the lack of nitrates. Overall, the rates indicate that greater amounts of denitrification could be accomplished if media is placed in the anoxic and aerobic zones of BNR systems.

The total denitrification comparisons between the IFAS and Control systems listed in Table 9 confirm statistically that there was no significant improvement in the total amount of dentrification accomplished by the IFAS systems relative to the Control at the two COD/TP ratio for the operating conditions used. This was primarily because the systems were substrate limited for either COD or nitrates, or both. The mean total denitrification data in Table 9 show that higher total denitrification was achieved in all three systems when they were operated at the COD/TP ratio of 52 rather than the COD/TP ratio of 20. This was because more organic substrate was available for denitrification because EBPR was no longer competing for the substrate.

Table 7 Maximum specific denitrification rates by fixed film media biomass determined by batch tests during Phases II and III

Phase II Observations	NO3-N Denitrification rate, mg/L/hr				Biomass on Web, g VSS/ft^2				Specific denitrification rate, mg N/g VSS/h			
	IFAS 1		IFAS 2		IFAS 1		IFAS 2		IFAS 1		IFAS 2	
	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2
1	6.70	6.59	5.11	5.47	4.70	3.89	4.57	4.16	39.00	46.26	30.61	35.96
2	5.15	8.95	5.99	6.65	4.70	3.89	4.57	4.16	29.96	62.86	35.84	43.70
3	6.39	7.70	5.05	4.71	4.70	3.89	4.57	4.16	37.17	54.09	30.23	30.97
Average	6.08	7.75	5.38	5.61	4.70	3.89	4.57	4.16	35.38	54.40	32.23	36.87

Phase III Observations	NO3-N Denitrification rate, mg/L/hr				Biomass on Web, g VSS/ft^2				Specific denitrification rate, mg N/g VSS/h			
	IFAS 1		IFAS 2		IFAS 1		IFAS 2		IFAS 1		IFAS 2	
	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2	ANX 1	ANX 2
1	4.96	4.30	5.96	6.41	5.40	6.64	5.47	6.17	25.09	17.69	29.78	28.40
2	6.99	3.89	5.27	4.68	5.40	6.64	5.47	6.17	35.40	16.02	26.32	20.73
Average	5.97	4.10	5.62	5.55	5.40	6.64	5.47	6.17	30.25	16.86	28.05	24.57



	IFAS 1	Control	IFAS 2	IFAS 1	Control	IFAS 2	IFAS 1	Control	IFAS 2
Others	5.18	5.83	3.86	7.52	3.18	-1.06	1.52	3.43	1.05
Aerobic	4.86	-2.60	0.92	13.36	-0.78	13.67	29.87	0.00	36.86
Anoxic 2	5.44	5.22	6.54	10.48	23.13	6.52	10.25	8.78	6.70
Anoxic 1	82.79	89.48	84.73	51.92	46.71	56.04	54.40	73.30	51.73
Anaerobic 2	0.00	0.33	1.96	1.99	0.20	0.17	0.00	0.39	0.00
Anaerobic 1	1.73	1.73	1.99	14.72	27.56	24.65	3.95	14.09	3.67

Figure 8: Denitrification fraction by location in each system during Phase I, II, and III experiments

Table 8 Distribution of denitrification by location in each system during Phase I, II, and III experiments

Location	Phase I (g/day)			Phase II (g/day)			Phase III (g/day)		
	IFAS 1	Control	IFAS 2	IFAS 1	Control	IFAS 2	IFAS 1	Control	IFAS 2
Anaerobic 1	0.11	0.11	0.13	1.36	2.23	2.08	0.44	1.54	0.40
Anaerobic 2	0.00	0.02	0.13	0.18	0.02	0.01	0.00	0.04	0.00
Anoxic 1	5.41	5.75	5.43	4.79	3.78	4.72	6.09	7.21	5.65
Anoxic 2	0.36	0.34	0.42	0.97	1.87	0.55	1.15	1.78	0.73
Aerobic	0.32	-0.17	0.06	1.23	-0.06	1.15	3.35	0.00	4.02
Others	0.34	0.37	0.25	0.69	0.26	-0.09	0.17	0.38	0.11

Table 9 Analysis of variance with total denitrification as a response parameter

Analysis of Variance Table for Denitrification

Source Term	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power (Alpha = 0.05)
A: COD/TP Ratio	1	40.378	40.378	75.340	0.000*	1.000
B: Pilot system	2	2.991	1.496	2.790	0.088	0.480
AB	2	0.589	0.294	0.550	0.587	0.127
S	18	9.647	0.536			
Total (Adjusted)	23	53.605				
Total	24					
* Term significant at alpha = 0.05						
Means and Effects Section						
Term	**Count**	**Mean**	**Standard Error**	**Effect**		
All	24	9.875		9.875		
A: COD/TP Ratio						
20	12	8.578	0.211	-1.297		
52	12	11.173	0.211	1.297		
B: Pilot system						
Control	8	9.600	0.259	-0.275		
IFAS 1	8	10.374	0.259	0.498		
IFAS 2	8	9.653	0.259	-0.223		
AB: COD/TP Ratio,Pilot system						
20,Control	4	8.085	0.366	-0.218		
20,IFAS 1	4	9.220	0.366	0.143		
20,IFAS 2	4	8.430	0.366	0.075		
52,Control	4	11.115	0.366	0.218		
52,IFAS 1	4	11.528	0.366	-0.143		
52,IFAS 2	4	10.875	0.366	-0.075		

SUMMARY AND CONCLUSIONS

It was confirmed by statistical evaluation that during this study the BNR systems with fixed film media installed in the anoxic reactors did not accomplish greater denitrification and nitrogen removal than the Control system operated with media, but it was concluded that this was because the systems were underloaded with respect to either COD or nitrate for the experimental conditions used. However, it was possible to use the continuous flow data to show that denitrification in the first anoxic reactors of the IFAS systems were enhanced by the installation

of media because these reactors were not underloaded and could be separately analyzed. This result was confirmed by batch test determinations of the denitrification rates of the biofilms grown on the Accuweb® media. Additional conclusions developed from an analysis of the data developed during the study are as follows:

1. Installation of fixed film media into the anoxic and/or aerobic reactors of the BNR systems caused significance changes in the biomass distribution within the systems, and resulted in a decrease in the MLVSS concentration in all reactors. In particular, this resulted in a decrease in the MLVSS concentrations in the anaerobic zone, and therefore, in the EBPR anaerobic mass fraction. This apparently was responsible for a reduction in the amount of phosphorus removal accomplished by the IFAS systems relative to the Control.
2. Fixed film media in the anoxic reactors reduced the amount of excess biomass maintained and produced by the IFAS systems relative to the Control. However, media in the aerobic reactors increased the amount of biomass in the systems and increased the amount of waste biomass produced.
3. Installation of fixed film media into the systems resulted in significant denitrification in the aerobic zones. As much as 30% of the total dentrification was observed to occur in the aerobic zone of IFAS 1 and 37% in IFAS 2, even though IFAS 1 did not have media installed in the aerobic zone. It is possible that denitrifiers sloughed off of the anoxic zone media and became part of mixed liquor suspended solids, resulting in higher fractions of active denitrifiers in the MLVSS aerobic zones. No denitrification was observed in the aerobic zone of the Control.
4. Decreasing the influent phosphorus concentration from 30 to 11 mg/L to change the COD/TP ratio from 20 to 52 increased the denitrification in the first anoxic reactors of all three systems, but EBPR was lost from all three systems and the IFAS systems failed to accomplish complete nitrification after the change was made. It was concluded that the Control system lost EBPR because of the excess recycle of nitrates whereas the IFAS systems lost EBPR because of 'washout' resulting from the low MLVSS concentrations at the low temperature and MCRT conditions. Apparently the nitrifiers also partially washed out.

5. Reducing the operating MCRT from 10 to 6 days caused small changes in the amount of substrates entering the first anoxic cells and stimulated additional denitrification without a loss of EBPR.
6. The experimental results in the studies indicate that activated sludge systems containing integrated Accuweb® media have a greater potential for denitrification than conventional BNR systems because the experimental IFAS systems had higher specific denitrification rates in the anoxic zones and accomplished substantially more denitrification in the aerobic zones than the Control system.

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CHAPTER 5: THE PERFORMANCE OF IFAS WASTEWATER TREATMENT PROCESSES FOR BIOLOGICAL PHOSPHORUS REMOVAL

T. SRIWIRIYARAT AND C.W. RANDALL*

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University, 418 Durham Hall, Blacksburg, VA 24061, USA

Abstract—

Integrated Fixed Film Activated Sludge (IFAS) is a promising process for the enhancement of nitrification and denitrification in conventional activated sludge systems that need to be upgraded for biological nutrient removal (BNR), particularly when they have space limitations or need modifications that will require large monetary expense. Several studies have reported successful implementation of IFAS at temperate zone wastewater treatment facilities, typically by placement of fixed film media into aerobic zones (WERF Report, 2000). However, nearly all of the implementations have not included enhanced biological phosphorus removal (EBPR) in the upgraded systems. This is possibly because the treatment plants have been operated at low mixed liquor mean cell residence times (MCRTs), and EBPR would wash out of the systems at the low temperatures encountered, making it difficult to maintain EBPR. The primary objective of this study was to investigate the incorporation of EBPR into IFAS systems, and study the interactions between the fixed biomass and the mixed liquor suspended solids with respect to substrate competition and nutrient removal efficiencies. Three pilot-scale UCT/VIP configuration systems were used, one as a control and the other two with Accuweb media integrated into some of the anoxic and aerobic reactors. The systems were operated at different MCRTs,and influent COD/TP ratios, and with split influent flow. The experimental results confirmed that EBPR can be incorporated successfully into IFAS systems, but the redistribution of biomass resulting from the integration of fixed film media, and the competition for organic substrate between EBPR and denitrification will affect performance. Also, the integration of fixed film media into the anoxic reactors affected performance differently from media in aerobic reactors.

Key words—Activated Sludge, BNR, EBPR, Biofilm, IFAS, Accuweb, COD/TP ratio, P release, P uptake, MCRT

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*Author to whom all correspondence should be addressed:

[Tel: 540-231-6018, Fax: 540-231-7916, E-mail: cliff@vt.edu]

INTRODUCTION

During the past decade, considerable research has investigated the benefits of integrating fixed film media into biological nutrient removal (BNR) activated sludge processes, with the primary objective of enhancing nitrification at low mixed liquor temperatures and mean cell residence times (MCRT) (Lessel, 1993; Mitta, 1994; Sen and Randall, 1994; Jensen, 1995; Sen; 1995; Liu, 1996). These studies have shown that nitrification can be significantly and successfully enhanced by utilization of integrated fixed film activated sludge (IFAS) systems. Furthermore, simultaneous denitrification in the aerobic zones with integrated fixed film media has been reported from both pilot-scale and full-scale IFAS wastewater treatment plants (Mitta, 1994; Sen and Randall, 1994; Jensen, 1995; Sen; 1995; Liu, 1996; Randall and Sen, 1996). However, none of these studies have included enhanced biological phosphorus removal (EBPR), even when anaerobic zones were included in the systems, apparently because of the very low suspended biomass MCRTs and temperature combinations used. It is known that EBPR will wash out of activated sludge systems before heterotrophic functions (McClintock, et al., 1991, Mamais and Jenkins, 1992) and that EBPR processes require that the biomass experience sequencing anaerobic and aerobic conditions. Therefore, EBPR by attached biomass would not be possible in most continuous flow BNR systems because the biomass is fixed in one location and typically cannot be subjected to alternating environmental conditions..

A few investigators have explored the interactions of EBPR and fixed film systems. One study attempted to implement EBPR in Sequencing Batch Reactors (SBR) systems containing fixed-film media (Garzon-Zuniga and Gonzalez-Martinez., 1996). The SBR systems were filled with Pall-Rings with a total biofilm surface area of 54 m^2 and evaluated at different organic loadings,

cycle durations and aerobic HRTs. The optimum performances as indicated by experimental results for simultaneous organic carbon, nitrogen, and phosphorus removal were achieved at 3 g COD/m^2/day organic loading using a 24 hour recycle period. The alternating ratio of anaerobic/aerobic conditions of 1.0/1.0 provided the best results. The organic loading maintained was less than 5 g COD/m^2/day, corresponding to a COD/PO4-P ratio of 16. Helness and Ødegaard (1999) concluded that good and stable EBPR could be achieved in a 10 L moving bed biofilm SBR filled with 53% by volume KMT-media, if it was subjected to alternating anaerobic and aerobic conditions. The factors affecting EBPR were the length of the anaerobic period, which must be long enough to completely remove the readily biodegradable COD, and the COD loading rates, which must be high enough for growth of biomass in the reactor. They concluded that the EBPR potential in hybrid biofilm/activated sludge systems was likely to be as good as in purely suspended growth activated sludge systems. Thus, although it is very unlikely that EBPR would be possible by biofilms growing in continuous-flow BNR systems with fixed environmental zones, it is reasonable that EBPR could be maintained in IFAS systems where much of the biomass is in suspended form and circulates throughout the system. The objective of this research was to demonstrate the ability of such systems to accomplish EBPR, and to determine how the presence of fixed-film growth affects the efficiency of EBPR and its interactions with other BNR processes.

MATERIALS AND METHODS

Pilot Plant Systems

Three pilot UCT/VIP configuration BNR wastewater treatment systems, referred to hereafter as IFAS 1, IFAS 2, and Control, were setup in a small building located adjacent to a sewer manhole on the Virginia Tech campus at Blacksburg Virginia. Each system was comprised of two anaerobic (7.6 L ea.), two anoxic (7.6 L ea.) and three aerobic (22.1 L ea.) reactors, and a clarifier. The wastewater was the combined Blacksburg, VA and Virginia Tech campus sewage flow, and it was pumped each day and stored in the building for 24 hours to acclimate it to the experimental temperature of 10±1 ^oC, and permit some fermentation. The sewage strength was then increased by the addition of sodium acetate, urea, and potassium dihydrogenphosphate, and so that the phosphorus concentration could be changed to obtain different COD/TP ratios for the experiments. The flow rate of the adjusted wastewater was 175 L/day to each system resulting in

a nominal HRT of 13±1 hours. The experiments were implemented in three phases based on media location, media quantity, COD/TP ratios, and MCRT. The 1-inch type of Accuweb© media was chosen as the fixed-film media for investigation throughout this study.

Phase I: This set of experiments was a preliminary investigation to evaluate EBPR performances in the IFAS and control systems at the relatively high MCRT of 10 days. Also, the competition for substrate between Bio-P bacteria and denitrifying bacteria, in IFAS systems with media in the anoxic reactors was investigated by splitting the influent flow 50-50 between the first anaerobic and first anoxic reactors of the Control and one of the IFAS systems. The other IFAS system received 100% of the influent flow into the first anaerobic reactor.

As shown in Figure 1, 0.3 ft^2 of 1-inch Accuweb media was installed into both anoxic reactors of IFAS 1. An additional 1.4 ft^2 of Accuweb were installed into each of the first two aerobic reactors of IFAS 1 in an effort to enhance nitrification and denitrification in the aerobic zone. The influent to this system was split 50-50 between the first anaerobic and the first anoxic reactors. The mixed liquor suspended solids in the anoxic reactors with integrated Accuweb media racks were mixed using single axis mechanical mixers with two propellers, one located below the racks and one above the racks. This system was used to investigate EBPR performance when the influent flow was split to enhance denitrification in a system with fixed film media installed in the anoxic zone. The IFAS 2 system was operated with 100 % of the influent flow entering the first anaerobic cell and no media installed in the anoxic zone. Instead, 2.1 ft^2 of Accuweb media was installed in each of the second and third aerobic reactors. The Control system was a conventional UCT/VIP BNR activated sludge system operated without any integrated media.

The COD/TP ratio was maintained at an average of 18.02±2.57 during Phase I to enrich the Bio-P bacteria population and enable EBPR evaluation. The average COD/TKN ratio was 8.60±0.93. The raw domestic wastewater strength was increased to an average of 604.50±40 mg COD/L, 72 ±6.2 mg N/L, and 34 ±2.8 mg P/L.

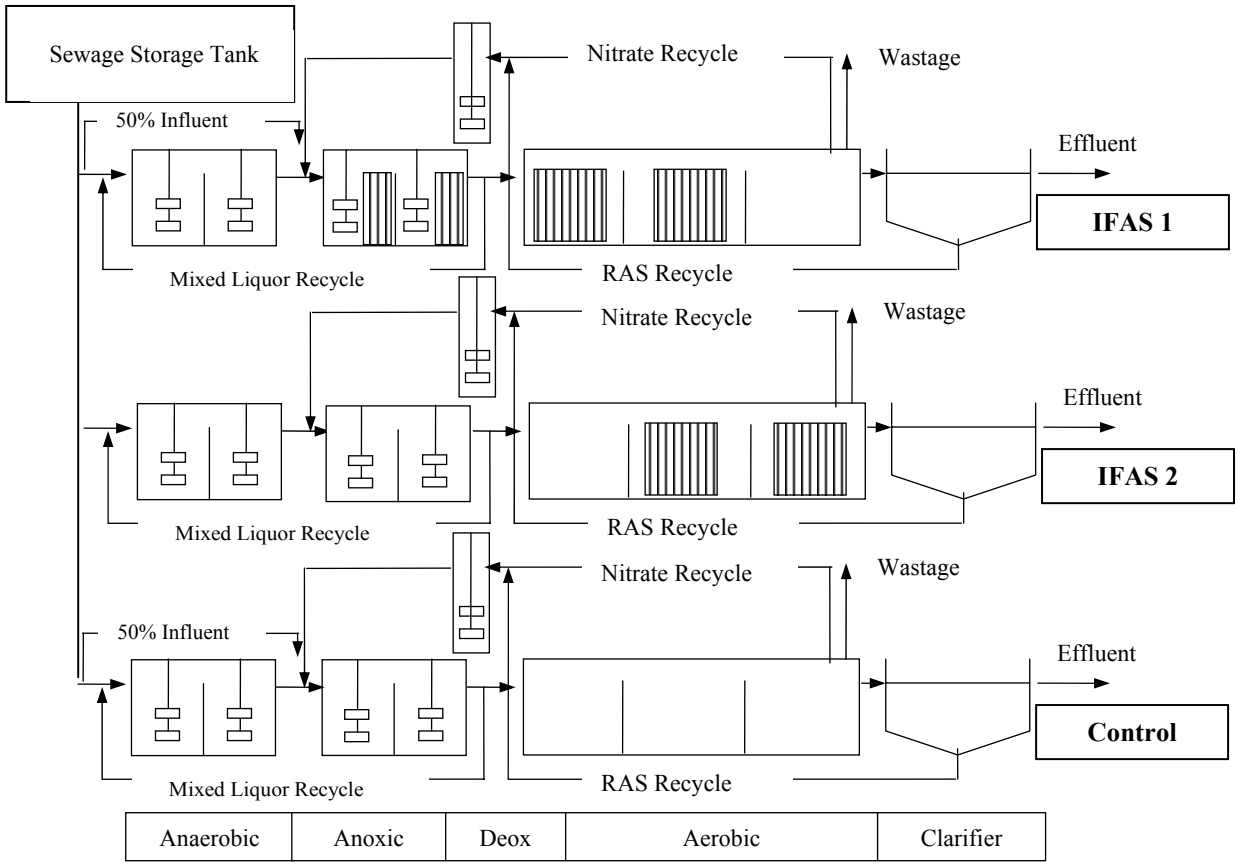


Figure 1. Schematic of pilot plants in experiment phase I

Phase II: For this phase, the MCRT was reduced to 6 days (~4.7 days aerobic MCRT) to see if EBPR could be maintained in the IFAS systems at the 10°C- 6d MCRT combination. The COD/TP ratio for this phase was 20, and the IFAS systems were modified as illustrated in Figure 2. The use of split flow was abandoned because it failed to significantly enhance denitrification during Phase I. Instead 100% of the influent flow entered the first anaerobic reactor of all three systems. The amount of Accuweb© media in the anoxic reactors of the two IFAS systems was the same as during Phase I, but only IFAS 2 had any media in the aerobic zone and it was in the middle reactor. The nitrate (NR) and returned activated sludge (RAS) recycles were both operated at 150% of influent flow (Q_{in}) for all three systems while mixed liquor recycle from the second anoxic to the first anaerobic was maintained at 100%Q_{in}. Therefore, the total recycle flow to the first anoxic of each system was about 500%Q_{in}. The strength of the sewage was increased to averages of 675 ±66 mg COD/L, 102.9 ±7.4 mg N/L, and 33.5 ±0.8 mgP/L. The total nitrogen was increased because the results of Phase I indicated that all systems were

underloaded with respect to nitrogen. As a result, the average COD/TP ratio was 20.1 ±2.3 and the average COD/TKN was 6.6 ±0.6 throughout Phase II.

Phase III: The experimental conditions during Phase III were designed to be similar to those of Phase II, except the COD/TP ratio was increased to 52 by decreasing the influent phosphorus concentration from 33.5 mgP/L to 11.1 mgP/L, to evaluate the effects of phosphorus limiting rather than COD limiting conditions on EBPR in the IFAS systems. Also, the NR and RAS recycles were increased to about 200%Q_{in} to prevent nitrate limitation in the anoxic zone, because higher rates of denitrification were expected with the increased COD/TP ratio. The measured average composition of the influent wastewater was 589 ±21 mg COD/L, 111.7 ±4.2 mg N/L total nitrogen, and 11.1 ±0.8 mg P/L total phosphorus. Thus, the average COD/TP ratio was 52.4±3.9, and the average COD/TKN was 5.2±0.2.

Analytical Methods

Parameters such as COD, TKN, TP, MLSS, MLVSS, pH, DO were measured in accordance with procedures outlined in Standard Methods for the Examination of Water and Wastewater, 19th Edition, 1995). Anions (nitrite, nitrate, phosphate, and sulfate) were analyzed using a Dionex 120 ion chromatography (Dionex Corp.,Sunnyvale, CA).

The growth on the media at steady state was measured by oven drying the media web taken from the anoxic and aerobic reactors at 105 ^{o}C for at least 24 hours after first draining free water for 1 hour and determining the wet weight of the media web (A). The combined biomass and media web were reweighed (B) after drying and subtracted from the wet weight to determine the amount of water entrained in the web and biomass (A-B). After all the dried biomass was removed from the media web, the weight of the media web was measured (C). The difference in weight (B-C) was considered to be the amount of dried biomass that grew on the media web. Dried biomass samples were randomly selected and were ignited at 550 ^{o}C for 20 minutes in accordance with Standard Methods (APHA, 1995). The percentage of volatile solids was determined and used to calculate the total volatile solids on the media web at steady state.

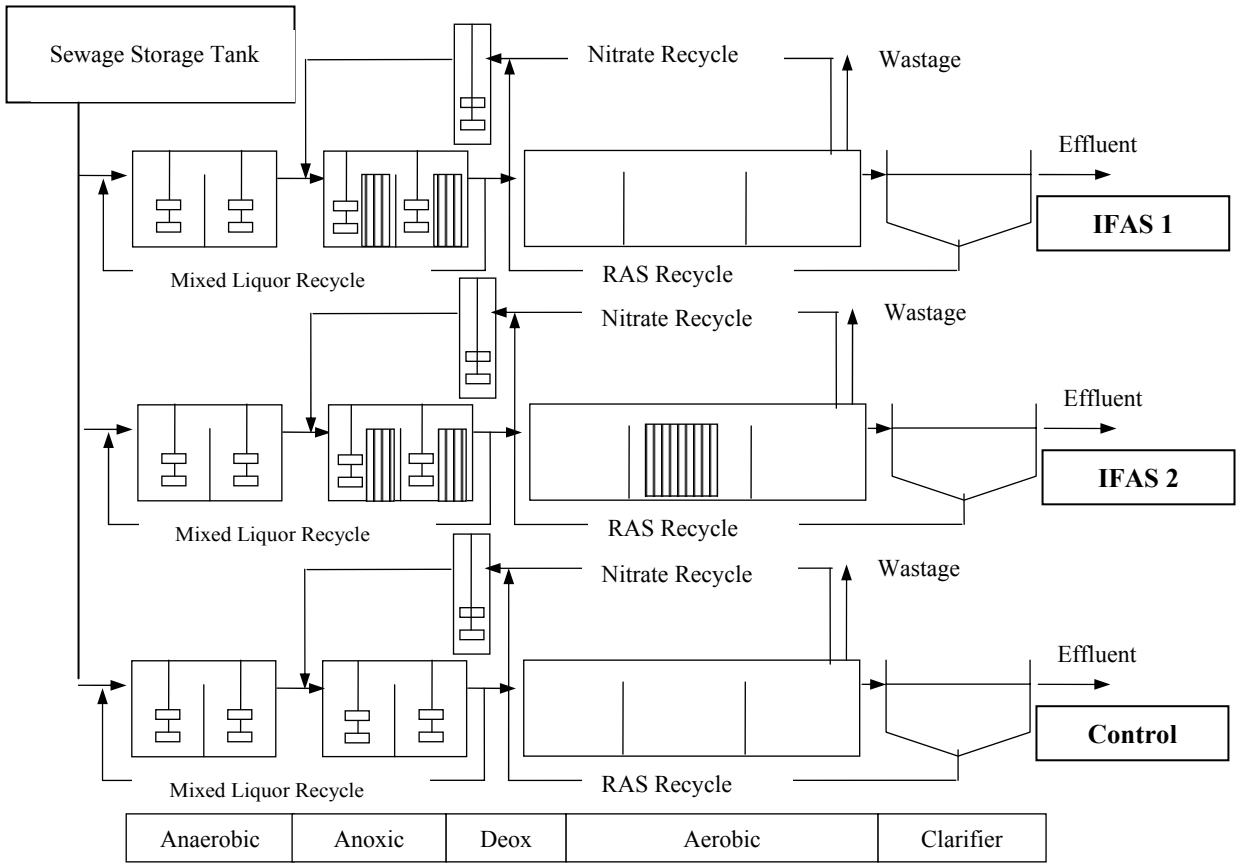


Figure 2. Schematic of pilot IFAS and Control systems for experiments phase II and III

RESULTS AND DISCUSSION

Biomass growth on the fixed film media in the IFAS systems resulted in significant biomass re-distributions in the reactors compared to the Control, and affected the total amounts of biomass maintained in the systems. The reactors selected for media placement affected both the concentrations and amounts of biomass in all of the reactors, and the total amount of biomass maintained in the two systems. The distributions of biomass in the reactors of all three systems for all three phases are given in Table 1. The results are expressed as volatile solids (VS) because robust EBPR systems considerably increase the total biomass by increasing the amounts of inorganic matter inside the cells, i.e. phosphorus, magnesium and potassium. It was assumed that VS determinations would not measure the inorganics and any differences in VS would reflex metabolic differences in the three systems. Also, the biofilm solids were converted to volatile suspended solids (VSS) for addition with the activated sludge mixed liquor volatile suspended solids (MLVSS) so that the biomass concentrations could be expressed uniformally.

Table 1 Changes in reactor biomass amounts and total system amounts with installation of fixed film media

System	Total Biomass, MLVSS + Fixed Film, expressed as MLVSS, mg/L							System
	Ana. 1	Ana. 2	Anoxic 1	Anoxic 2	Aerobic 1	Aerobic 2	Aerobic 3	Total, g
	PHASE I							
IFAS 1	(2298)	2298	**3496**	**3496**	**4336**	**4040**	3133	**321.8**
IFAS 2	(1983)	1983	(3430)	3430	(3525)	**5471**	**4462**	**343.6**
Control	(2503)	2503	(3630)	3630	(3527)	(3424)	3320	**320.2**
	PHASE II							
IFAS 1	(1558)	1558	**3230**	**3200**	(2865)	(2671)	2478	**246.9**
IFAS 2	(1400)	1400	**2510**	**2495**	(2448)	**4169**	2353	**249.4**
Control	(1808)	1808	(3203)	3203	(3056)	(2910)	2763	**269.1**
	PHASE III							
IFAS 1	(973)	973	**2083**	**2097**	(1997)	(1896)	1796	**170.5**
IFAS 2	(1114)	1114	**2122**	**2148**	(2054)	**3157**	1866	**199.4**
Control	(1276)	1276	(2312)	2312	(2314)	(2316)	2318	**208.0**

( ) estimated values **Values in bold include fixed film biomass**

The data in Table 1 indicates that integration of fixed film media into the anoxic reactors decreased biomass production by the BNR systems whereas media in the aerobic reactors increased biomass production. Both IFAS systems had media in two aerobic reactors during Phase I, and both produced more biomass than the Control system, but IFAS 1 with anoxic media produced considerably less biomass than IFAS 2 without anoxic media, and only marginally more than the Control. The relatively small anoxic volume of IFAS 1 (15.2 L) nearly offset the increase in sludge production by the large aerobic volume (36.9 L) of IFAS 1. During Phases II & III, both IFAS systems had media in both anoxic reactors, and both produced less biomass than the Control system, but IFAS 2 with media in one aerobic reactor produced more biomass than IFAS 1 which had anoxic media only. Also, the data clearly show that installation of fixed film media reduced the amounts of MLVSS maintained in the IFAS anaerobic reactors relative to the Control system, thereby reducing the anaerobic mass fraction of the IFAS systems, and possibly limiting their potential for EBPR relative to the Control system. It also can be

stated that integrating fixed film media into any of the reactors decreased the MLVSS concentrations in all of the other reactors relative to the Control and, during Phase III, after EBPR was lost, the Control had higher biomass concentrations in its anoxic reactors than the anoxic reactors of either of the IFAS systems, where biomass was growing on media in addition to be present in suspended form.

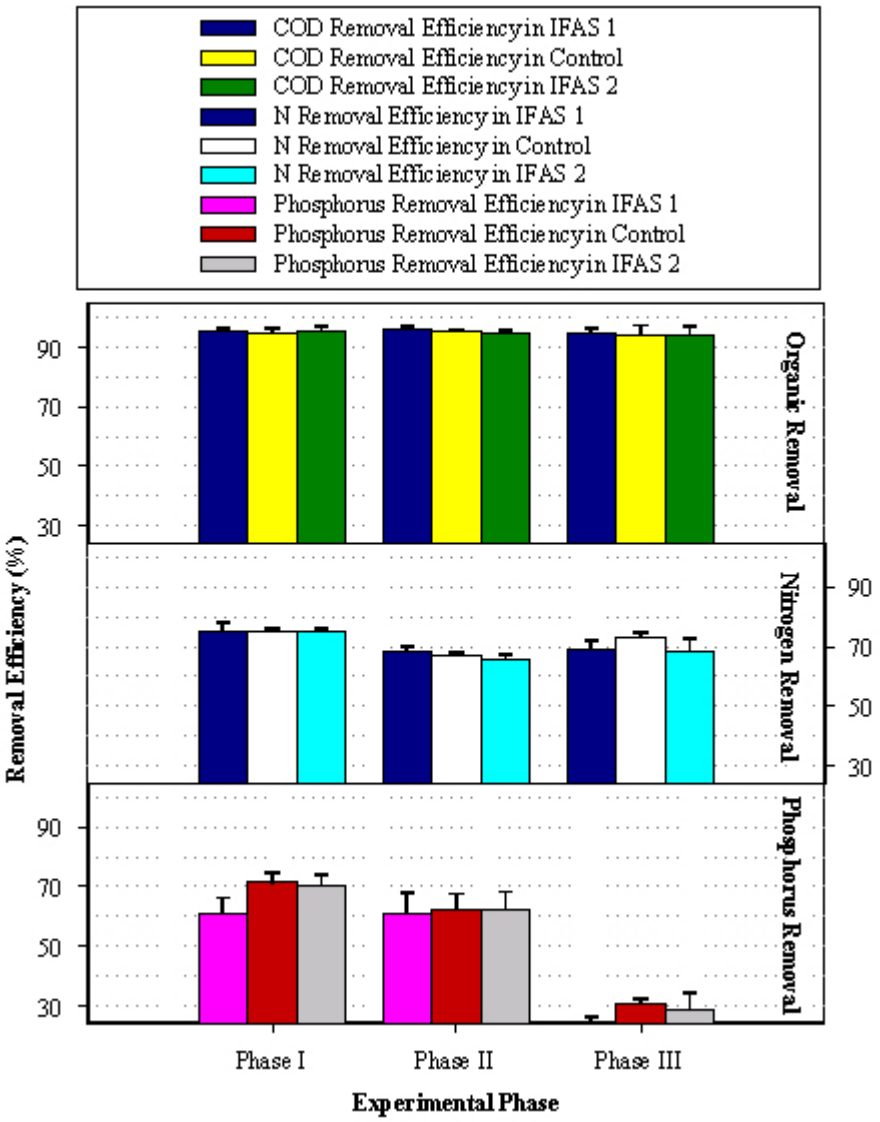


Figure 3: COD, nitrogen, and phosphorus removal efficiencies during phase I, II, III

The COD, nitrogen (N) and phosphorus (P) removal efficiencies observed at steady state during the three experimental phases are shown in Figure 3. The average substance concentrations and their standard deviations were summarized in Sriwiriyarat and Randall (2002a and 2002b). The

data show that the experimental operating conditions of the three phases had almost no effect on the COD removal efficiency, and only modest effects on the nitrogen removal efficiency. However, the effects on EBPR efficiencies were substantial between systems within Phase I and between Phases I and II. Then EBPR was lost altogether in all three systems during Phase III. The effects of the Phase I conditions (10 d total MCRT, 10^{o}C, etc.) on EBPR were different for all three of the systems. The Control system accomplished 70% phosphorus removal efficiency (10.2 mgP/L effluent) with the influent flow split 50-50 between the first anaerobic and the first anoxic reactors, whereas IFAS 1 with the same influent flow split accomplished only 60% P removal (13.6 mgP/L effluent). The P removal by IFAS 2 was equal to the removal efficiency of the Control (70%, 10.2 mgP/L effluent), but the first anaerobic reactor of IFAS 2 received 100% of the influent instead of 50%, thereby providing the bacteria in the anaerobic zone with more readily biodegradable substrate than in the Control. The recycle of nitrates back to the anaerobic reactors was insignificant for all three systems during Phase I. From the results it can be concluded that P removal can be accomplished in IFAS systems, but P removal was more efficient per unit biodegradable COD utilized in the Control system than in either IFAS system when all were operated at 10^{o}C with a MCRT of 10 days and an influent COD/TP ratio of 18.

The Phase II experiments also demonstrated that EBPR can be maintained in IFAS systems down to overall MCRTs of 6 days (4.7 days aerobic MCRTs), but further indicated that IFAS EBPR is likely to be less robust than in conventional three stage BNR systems. The phosphorus removal efficiencies of both the Control and IFAS 2 systems decreased by nearly 10 percent from Phase I to Phase II when the MCRT was decreased from 10 days to 6 days. During Phase II, 100% of the influent entered the anaerobic zone of all three systems, which was a change for IFAS 1 and the Control but not for IFAS 2. Therefore, it was not surprising that IFAS 2 EBPR decreased, but it was a surprise that the Control EBPR decreased. Inspection of the data showed that substantial amounts of nitrates were cycled back to the anaerobic zones of all three systems during this phase, which reduced the amounts of readily biodegradable organics available for EBPR, and, therefore, the amounts of EBPR accomplished. The amounts of nitrates cycled back in the Control and IFAS 2 systems were approximately the same, but the amount cycled back in IFAS 1 was about 40% less. Coincidentally, the drop in % phosphorus removal was the same in IFAS 2 as in the Control, indicating that the MCRT change had a lesser effect on the IFAS

system, because the influent biodegradable organics to IFAS 2 were not substantially increased by the Phase II conditions relative to Phase I as they were to the Control system. Apparently the competing effects on EBPR of MCRT decrease and additional biodegradable organics to the anaerobic zone exactly compensated each other in the IFAS 1 system because the phosphorus removal was the same during Phase II as was observed during Phase I. It is highly likely that the increase in the % influent to the anaerobic zone would have caused a positive stimulation of EBPR had nitrate recycle to the anaerobic zone been prevented. Thus, when 100% of the influent was entering the anaerobic zones, all three systems accomplished approximately the same amount of EBPR, i.e. 60% removal, even though the biomass amounts maintained in the anaerobic zones were quite different. The IFAS 2 system had 23% less biomass than the Control system, and IFAS 1 had 14% less. It appears that EBPR performance is relatively insensitive to the quantity of biomass maintained in the anaerobic zone, but the interpretation is complicated by the amounts of oxidized nitrogen that were recycled back to the anaerobic zones.

During Phase III phosphorus removal decreased by 50 percent or more in all three systems when the influent phosphorus was decreased from 33.5 to 11.1 mg/L and the influent COD was reduced from 675 to 589 mg/L to increase the influent COD/TP ratio from 20 to 52. All indications were that EBPR washed out of all three systems and that EBPR had completely ceased to function within 30 days of making the influent changes when all other operating conditions were maintained the same. The failure of EBPR could not be attributed to phosphorus limitation because the measurable amounts of phosphorus exceeded 7.5 mg P/L in the effluents of all three systems. The intent of increasing the COD/TP from 20 to 52, i.e. establishing phosphorus limiting conditions, was to reduce the amount of COD that would be used for EBPR so that more would be available for the denitrifiers, but the change had a substantially greater effect on EBPR performance than expected.

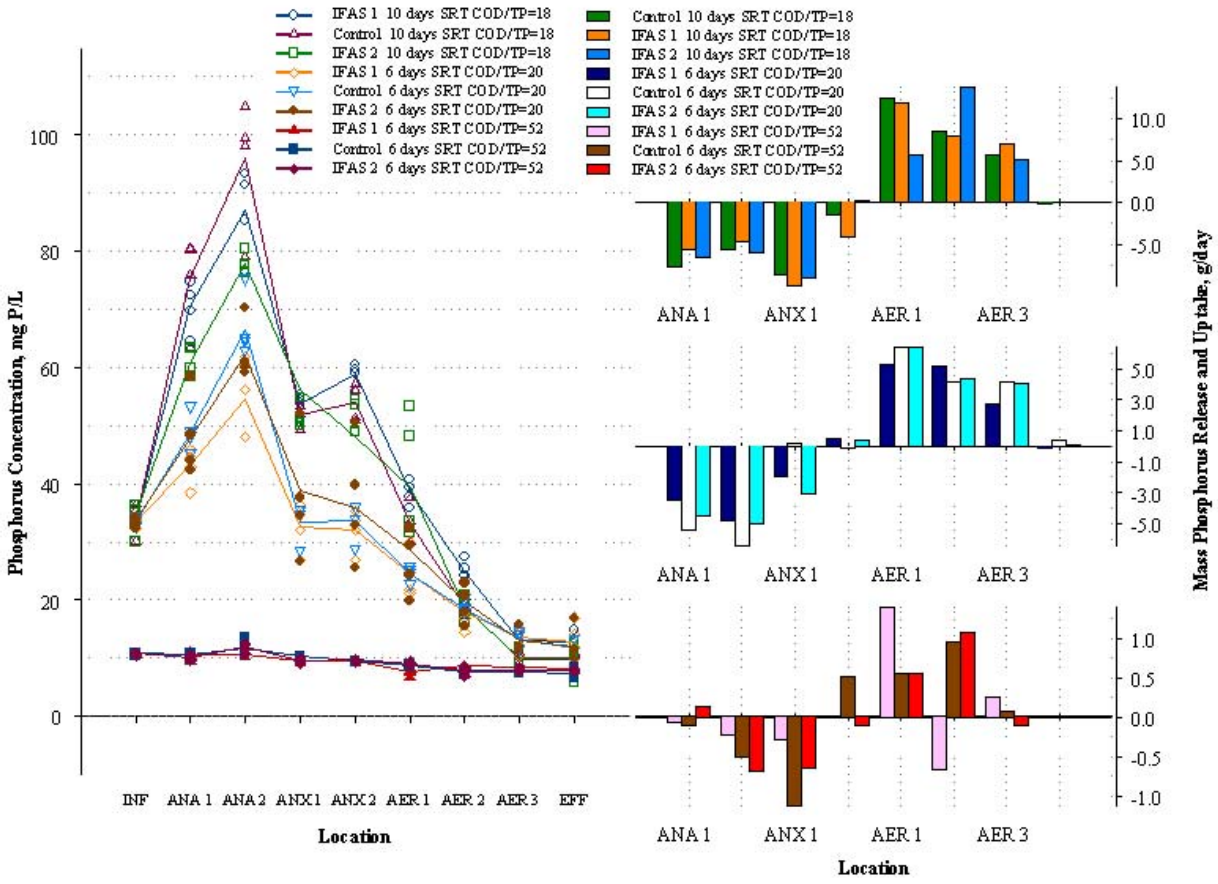


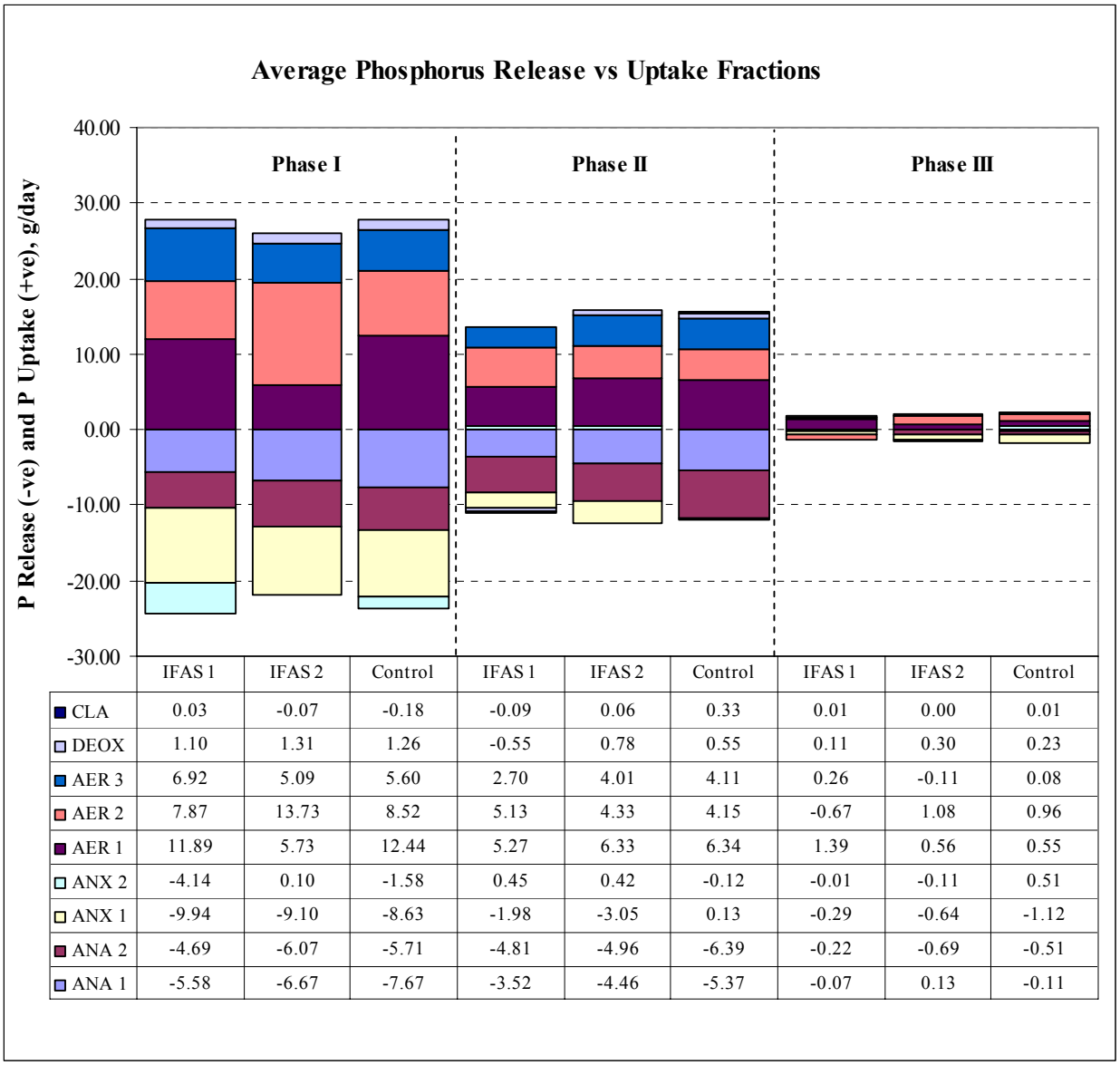
Figure 4: Phosphorus removal performances and mass balances in IFAS and control systems in phase I, II, III

Figure 4 shows the profiles of average orthophosphate concentration along with the average TP mass balance around each reactor during Phases I, II, and III. The TP mass balance was used to provide more accurate information regarding the actual phosphorus release and uptake that occurred in the different reactors. The same pH range was maintained in all three systems so that accurate comparisons of phosphorus release and uptake could be made. The profiles in Figure 4 show that the Control system had the highest anaerobic zone phosphorus releases during all three experimental phases, but Table 2 indicates that the average total phosphorus releases were approximately the same in all three systems. This is because phosphorus releases took place at different locations in the anoxic zones as well as the anaerobic zones of the systems as illustrated in Figure 5.

During Phase I, more phosphorus release was observed in IFAS 1 which had fixed film media installed in the anoxic tanks than in the IFAS 2 system, which had only aerobic zone media. This is because both the influent flows to IFAS 1 and the Control were split 50-50 between the first anaerobic and first anoxic reactors, and a lot of readily biodegradable COD was entering the anoxic zones of these two systems. However, the additional phosphorus released in the second anoxic reactors of IFAS 1 was not taken up by microorganisms in the aerobic reactors as much as in the Control system, probably because some of the phosphorus released in the anoxic zone of IFAS 1 was released by fixed film biomass that could not flow to the aerobic zone where the stored organics could be used for phosphorus uptake, which resulted in higher phosphorus concentrations in the IFAS 1 effluent. By contrast, in IFAS 2, all of the substrate entered the first anaerobic reactor, and very little readily biodegradable COD entered the anoxic zone, and the biomass from the anaerobic zone with the stored organics flowed on to the aerobic zone where the stored organics (PHAs) were used to take up phosphorus. The IFAS 2 system also had the highest phosphorus uptake in the second cell of the aerobic zone where as the highest phosphorus uptake in the IFAS 1 and Control systems was at the first cell of the aerobic zone. When all three systems were fed 100% of the influents into first anaerobic cells in phase II, they all had similar patterns of phosphorus uptake in the aerobic zones.

Table 2: Average phosphorus release and uptake in phase I, II, and III

P Behavior	Phase I			Phase II			Phase III		
	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control
Release (-ve)	-24.34	-21.90	-23.76	-10.94	-12.46	-11.87	-1.26	-1.42	-1.73
Uptake (+ve)	27.82	25.97	27.81	13.55	15.93	15.61	1.77	1.94	2.34



	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control	IFAS 1	IFAS 2	Control
CLA	0.03	-0.07	-0.18	-0.09	0.06	0.33	0.01	0.00	0.01
DEOX	1.10	1.31	1.26	-0.55	0.78	0.55	0.11	0.30	0.23
AER 3	6.92	5.09	5.60	2.70	4.01	4.11	0.26	-0.11	0.08
AER 2	7.87	13.73	8.52	5.13	4.33	4.15	-0.67	1.08	0.96
AER 1	11.89	5.73	12.44	5.27	6.33	6.34	1.39	0.56	0.55
ANX 2	-4.14	0.10	-1.58	0.45	0.42	-0.12	-0.01	-0.11	0.51
ANX 1	-9.94	-9.10	-8.63	-1.98	-3.05	0.13	-0.29	-0.64	-1.12
ANA 2	-4.69	-6.07	-5.71	-4.81	-4.96	-6.39	-0.22	-0.69	-0.51
ANA 1	-5.58	-6.67	-7.67	-3.52	-4.46	-5.37	-0.07	0.13	-0.11

Figure 5: P release (-ve) and P uptake (+ve) in all reactors during phase I, II, III.

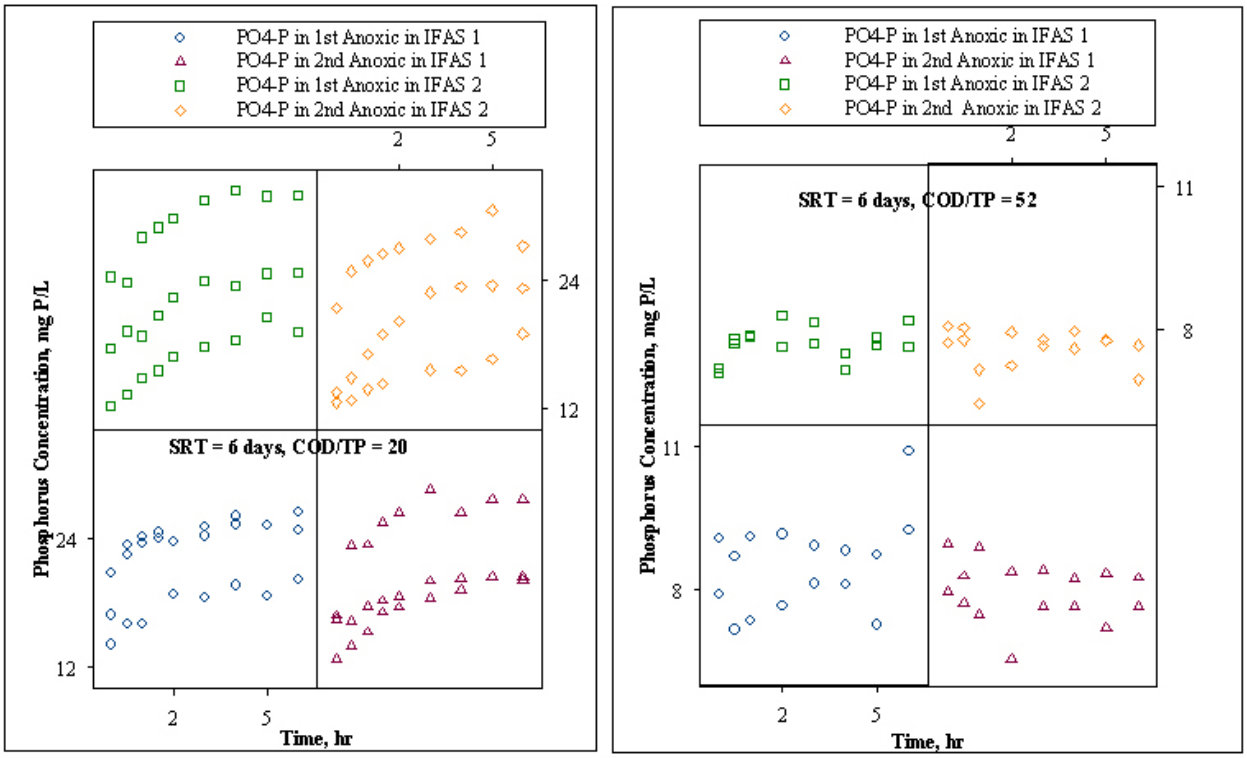


Figure 6: Changes in phosphorus concentrations with time in batch tests during phase II and III

Figure 6 illustrates the phosphorus released by the fixed film biomass attached to the media in the anoxic zones as observed during the batch tests. With the pH controlled and the fixed film media submerged in the effluents of the Phase II experiment, the phosphorus was released at the rates of 0.69 mg P/L/hr in the first anoxic reactor and 0.98 mg P/L/hr in the second anoxic reactor of IFAS 1. The IFAS 2 anoxic media had higher overall rates of 1.00 mg P/L/hr in the first anoxic reactor and 0.96 mg P/L/hr in the second anoxic reactor. In contrast, the phosphorus concentrations were nearly constant during the Phase III batch tests, further indicating that EBPR was no longer functioning in the BNR systems. In summary, the attached biomass in the anoxic reactors contributed to phosphorus release in the IFAS systems during the Phase I and II experiments, i.e. when EBPR was maintained in the systems, but this reduced the EBPR efficiency.

The amounts of biomass attached to the Accuweb® media during the experiments are shown in Table 3.

Table 3: Amounts of biomass attached to the Accuweb® media in the IFAS anoxic zones

Location	IFAS 1 (g/ft^2)					
	Phase I		Phase II		Phase III	
	MLVSS	MLSS	MLVSS	MLSS	MLVSS	MLSS
ANX 1	7.18	10.09	4.70	5.99	5.40	6.64
ANX 2			3.89	4.88	5.78	7.04
AER 1	19.08	25.01	0.00	0.00	0.00	0.00
AER 2	14.38	17.48	0.00	0.00	0.00	0.00
AER 3	0.00	0.00	0.00	0.00	0.00	0.00
Location	IFAS 2 (g/ft^2)					
	Phase I		Phase II		Phase III	
	MLVSS	MLSS	MLVSS	MLSS	MLVSS	MLSS
ANX 1	0.00	0.00	4.57	5.91	5.47	6.56
ANX 2	0.00	0.00	4.16	5.48	6.17	7.52
AER 1	0.00	0.00	0.00	0.00	0.00	0.00
AER 2	18.40	23.03	12.97	16.67	8.78	10.73
AER 3	17.87	23.42	0.00	0.00	0.00	0.00

Figure 7 illustrates the consistency of the relationships between phosphorus release and uptake which were observed in the pilot systems during the experimental runs. The best phosphorus release and uptake was observed when the systems were operated at a 10 day MCRT with a COD/TP of 18, i.e. in phase I. The release and uptake of phosphorus were reduced when the system MCRTs were lowered to 6 days for the Phase II experiments, and, during Phase III, EBPR washed out of all three systems at the day MCRT when the COD/TP was increased to 52 by lowering the influent phosphorus concentration.

The average Phase I net phosphorus uptakes, shown in Figure 8, were measured as 20.96 mg P/L, 23.68 mg P/L, and 23.85 mg P/L in IFAS 1, IFAS 2, and Control systems, respectively. The average amount of phosphorus release in IFAS 1 was the same as in the other two systems, but the net phosphorus uptake was lower, as discussed in the preceding section. The average net phosphorus uptakes during Phase II were in the range of 20.32-21.61 mg P/L and approximately the same in all three systems. It is interesting to note that the net phosphorus uptake amounts were reduced very little when the MCRTs were decreased from 10 to 6 days, while the COD/TP ratio was maintained at approximately the same value, i.e. ≈ 20, but this apparently was because of the recycle of nitrates back to the anaerobic zones.

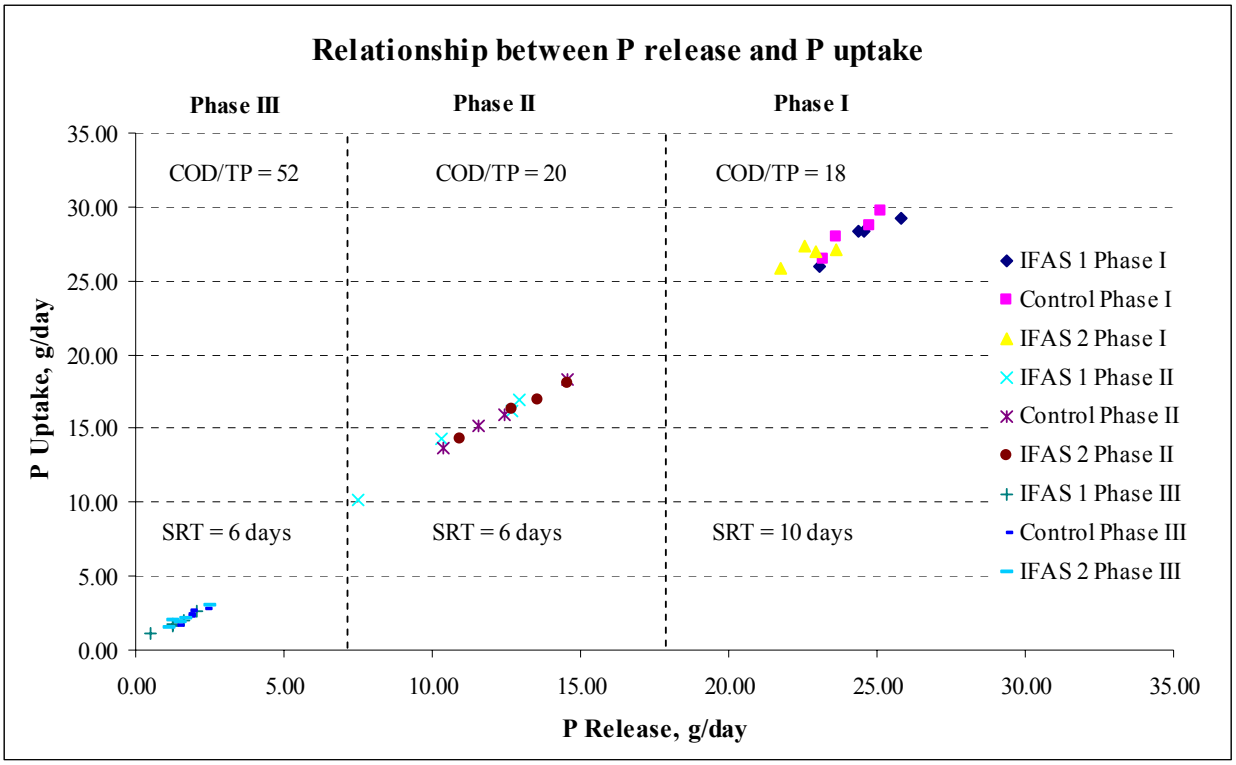


Figure 7: The relationship between P release and P uptake during Phases I, II and III

Tables 4 and 5 indicate that there was no statistical difference in net phosphorus uptake between the pilot systems during Phase I, II, and III at the significance level of 0.05 because of the integration of fixed film media into two of the systems, or because of interactions between the two COD/TP ratio used and the fixed film media installations. However, the statistical results report that the EBPR performance was significantly reduced by decreasing the influent phosphorus concentration from 33.5 to 11.1 to increase the COD/TP ratio to 52 for the Phase III experiments. Statistical evaluation of effluent phosphorus in the phase I experiments indicate that EBPR performance was reduced by adding substrates directly to the anoxic reactor where there was fixed film media installed.

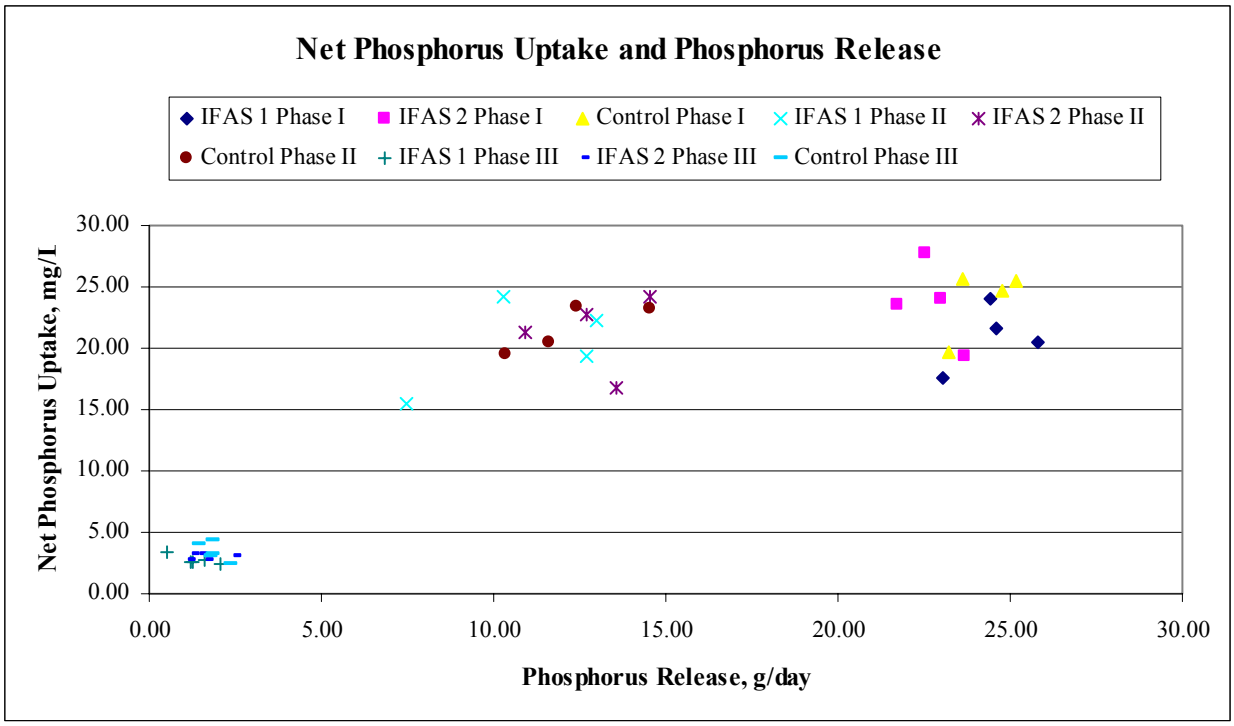


Figure 8: Net phosphorus uptake and total phosphorus release during Phases I, II, and III

In summary, EBPR performance was not significantly decreased or increased by the installation of fixed film media into the anoxic and aerobic reactors of the experimental three stage BNR systems for the experimental conditions used. The experimental results confirm that EBPR can be maintained in three stage IFAS systems and that integrating media into the anoxic and aerobic reactors, even though biomass growth on the media reduces the quantity of biomass maintained in the anaerobic zones. The performance on EBPR was also reduced if the influent flow was diverted to the anoxic zones in which fixed film media installed.

Table 4: Statistical evaluation of net phosphorus uptake and effluent phosphorus in the IFAS and Control systems.

Alternative Hypothesis	T-Value	Prob Level	Decision -5%	Power (Alpha=.05)	Power (Alpha=.01)
T-Test between IFAS 1 and Control on Net P Uptake in Phase I					
H_0: There is no difference in mean net P uptake between IFAS 1 and Control system					
H_A: There is difference in mean net P uptake between IFAS 1 and Control system					
Difference <> 0	1.4726	0.19129	Accept Ho	0.237861	0.071718
Difference < 0	1.4726	0.904355	Accept Ho	0.00148	0.000201
Difference > 0	1.4726	0.095645	Accept Ho	0.367618	0.123142
Difference: (Pilot system=Control)-(Pilot system=IFAS1)					
T-Test between IFAS 2 and Control on Net P Uptake in Phase I					
H_0: There is no difference in mean net P uptake between IFAS 2 and Control system					
H_A: There is difference in mean net P uptake between IFAS 2 and Control system					
Difference <> 0	0.0781	0.940312	Accept Ho	0.050506	0.010134
Difference < 0	0.0781	0.529844	Accept Ho	0.0432	0.008436
Difference > 0	0.0781	0.470156	Accept Ho	0.057621	0.011807
Difference: (Pilot system=Control)-(Pilot system=IFAS2)					
T-Test between IFAS 1 and Control on Effluent Phosphorus in Phase I					
H_0: There is no difference in mean effluent P between IFAS 1 and Control system					
H_A: There is difference in mean effluent P between IFAS 1 and Control system					
Difference <> 0	-2.799	0.031175	Reject Ho	0.648219	0.305899
Difference < 0	-2.7997	0.015588	Reject Ho	0.794516	0.442136
Difference > 0	-2.7997	0.984412	Accept Ho	0.000014	0.000002
Difference: (Pilot system=Control)-(Pilot system=IFAS1)					
T-Test between IFAS 2 and Control on Effluent Phosphorus in Phase I					
H_0: There is no difference in mean effluent P between IFAS 2 and Control system					
H_A: There is difference in mean effluent P between IFAS 2 and Control system					
Difference <> 0	-0.1039	0.920605	Accept Ho	0.050898	0.010238
Difference < 0	-0.1039	0.460303	Accept Ho	0.060337	0.012465
Difference > 0	-0.1039	0.539697	Accept Ho	0.041118	0.007967
Difference: (Pilot system=Control)-(Pilot system=IFAS2)					

Table 5: Analysis of variance for P uptake response for experiments in phase II, and III

Source Term	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power (Alpha = 0.05)
A: COD/TP Ratio	1	1941.481	1941.481	391.750	0.000000 *	1.000
B: Pilot system	2	4.113	2.057	0.420	0.666	0.107
AB	2	0.535	0.268	0.050	0.948	0.057
S	18	89.206	4.956			
Total (Adjusted)	23	2035.335				
Total	24					
* Term significant at alpha = 0.05						
Means and Effects Section						
Term	**Count**	**Mean**	**Standard Error**	**Effect**		
All	24	9.875		9.875		
All	24	12.068		12.068		
A: COD/TP Ratio						
20	12	21.062	0.643	8.994		
52	12	3.073	0.643	-8.994		
B: Pilot system						
Control	8	12.546	0.787	0.479		
IFAS 1	8	11.536	0.787	-0.531		
IFAS 2	8	12.120	0.787	0.053		
AB: COD/TP Ratio,Pilot system						
20,Control	4	21.613	1.113	0.072		
20,IFAS 1	4	20.323	1.113	-0.208		
20,IFAS 2	4	21.250	1.113	0.136		
52,Control	4	3.480	1.113	-0.072		
52,IFAS 1	4	2.750	1.113	0.208		
52,IFAS 2	4	2.990	1.113	-0.136		

SUMMARY AND CONCLUSIONS

The results of this investigation clearly show that EBPR can be successfully accomplished in three stage IFAS BNR systems. Reasonably robust EBPR was accomplished in systems with fixed film media installed in anoxic reactors only, in aerobic reactors only, and in both anoxic and aerobic reactors. It was statistically confirmed that EBPR could be maintained in the IFAS systems without serious complications, but EBPR by the Control system appeared to be a more efficient per unit COD utilized than the IFAS systems. Also, EBPR performance is likely to be reduced if the influent flow is split between the anaerobic and anoxic zones to enhance denitrification. The conclusions obtained from this study are listed as follows:

1. The EBPR performances in the IFAS process with media installed in the anoxic zone to which influent flow was diverted was about 10% than the Control system and the IFAS system operated without split flow. Apparently this is because the presence of readily biodegradable COD in the anoxic zone stimulated the attached biofilms to release phosphorus, but they could not flow to the aerobic zone where they could take up the released phosphorus during stored substrate utilization.
2. The phosphorus release and uptake took place in different amount in each location of each system. Even thought the net phosphorus release and uptake were similar in the IFAS and control systems, the IFAS process tends to have more P releases in the anoxic zones with fixed film media.
3. It appeared that the change in the COD/TP ratio had a greater impact on EBPR than changes in MCRT or the integration of media into the anoxic zones. The percent phosphorus removal decreased only 10% when the MCRT was changed from 10 days to 6 days, while decreased by 50% when the COD/TP ratio was changed from 20 to 52.
4. It is statistically confirmed that EBPR can be maintained in the IFAS systems. The performances in the IFAS system were the same as a conventional BNR system with the same configuration type and under the same operating conditions, but without intergrated media.

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CHAPTER 6: MATHEMATICAL MODELING OF IFAS BIOLOGICAL NUTRIENT REMOVAL WASTEWATER TREATMENT PROCESSES

T. SRIWIRIYARAT AND C.W. RANDALL*

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University, 418 Durham Hall, Blacksburg, VA 24061, USA

Abstract—

To ease the design and operation of the combined hybrid biofilm/activated sludge processes, referred to herein as Integrated Fixed Film Activated Sludge (IFAS) systems, a mathematical model becomes a necessary tool not only for research investigations, but also to facilitate design and operational applications by predicting system responses and optimized performance conditions. To develop the IFAS model described in this paper, the zero-dimensional biofilm model with theoretical equations was integrated with a widely accepted general activated sludge biological nutrient removal (BNR) model to link rapid computations of biofilm processes with reasonable predictions about biomass and substrate concentrations for the input and output from a mixed culture reactor. The major shortcoming of this approach is that it ignores the changes inside the biofilm, but, nevertheless, the method provides reasonable results when compared to experimental data. An IFAS simulator software was also developed in this study to implement the IFAS model and provide user-friendly and interactive software designed specifically for the IFAS processes. It can be used for simulation of both IFAS and conventional activated sludge BNR processes. The software is independent of generic simulators or other commercial simulation software; therefore, users do not need additional software to utilize this program for the design and operation of IFAS processes. The experimental data from conventional BNR and IFAS pilot-scale systems studies using Captor® and Accuweb® as integrated media were used as case studies in this article. The results from this IFAS simulator provided a reasonably good fit with IFAS-Captor® experimental data and provided predictions that were similar to those obtained from a previously developoed IFAS model that used empirical rather than theoretical equations. Given the same set of COD and nitrogen removal parameters and a few adjusted EBPR parameters, the IFAS model also provided reasonable predictions for the IFAS-Accuweb®

process and conventional BNR systems, but further calibrations of EBPR parameters are needed to provide better predictions. With the mechanistic IFAS model developed, it should be possible to apply the model with any type of fixed film media if the media characteristics are available.

Key words—IFAS, Biofilm, Model, Simulator, BNR, Zero-dimensional, Captor®, Accuweb®

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*Author to whom all correspondence should be addressed:

[Tel: 540-231-6018, Fax: 540-231-7916, E-mail: cliff@vt.edu]

INTRODUCTION

The introduction of biofilm media into suspended growth systems, referred to herein as Integrated Fixed Film Activated Sludge (IFAS) systems, is a potential method to enhance the capacity and reliability of wastewater treatment systems, especially for nitrification and denitrification. However, the complexities of these hybrid biofilm and suspended growth processes introduce numerous difficulties for scientists and engineers attempting to describe their interactions and design practical systems. Mathematical models are helpful and important tools for the design, optimization and operation of complex wastewater treatment processes, and proven reliable models are needed for the development and implementation of IFAS systems. They would allow prediction of the response variables and performances of IFAS systems and could be used to design optimized systems and develop operational criteria. Previous research at Virginia Tech developed a mathematical model specifically for IFAS processes that combined the basic equations for activated sludge processes with empirical equations developed from experiments with an IFAS system using Captor® sponges as fixed film media installed in the aerobic zone (Sen, 1995; Sen and Randall, 1996). The empirical equations were developed using batch test results to determine the kinetic coefficients using nonlinear regression methods. The simulations were conducted using a spreadsheet program and then the results were compared with the experimental data. The predictions obtained provided a good fit with the experimental results in the aerobic zone, but predicted substantially higher results for the anaerobic and anoxic zones because only basic processes were used for those segments of the

model. The anaerobic and anoxic zone problems were solved by Sriwiriyarat (1999) by including more complex activated sludge processes from IAWQ Model No. 1, and more complex wastewater characterization into Sen's IFAS model concepts. Additionally, user-friendly and interactive computer software was developed to replace the spreadsheet version of the model. Similarly, a simulation model has been developed specifically for IFAS in Japan to support a combined activated sludge and biofilm process for nitrogen and phosphorus removal by the so-called CAB/NP process. For this model, the biofilm processes and detachment mechanisms were integrated into the ASM Model 2. A transport mechanism for the movement of detached biofilm to suspended growth was a key concept of this model. Polyurethane plastic media was selected as a media carrier for this process. The simulation was conducted using the AQUASIM program (Suzuki, 1999).

In this article, the IFAS model initially developed by Sen (1995) and modified by Sriwiriyarat (1999) was further developed using the zero-dimensional biofilm model, the general model for biological nutrient removal (BNR) activated sludge systems, and interactions between the two models. The aim of this development is to provide fast, accurate IFAS system simulation computations in a user-friendly, interactive computer software package.

MODEL DEVELOPMENT

The applicable mathematical models can generally be categorized as the suspended growth model and the biofilm model according to the state of biological growth and are presented in the literature. The best known mechanistic model for suspended growth (activated sludge) systems is the one developed by the International Association on Water Quality (IAWQ) model. This model simulates carbon removal, nitrification, and denitrification and is known as Activated Sludge Model No.1 (ASM1). The enhanced biological phosphorus removal (EBPR) processes were subsequently incorporated into Activated Sludge Model No. 2 (ASM2). Many mathematical models have been developed for attached growth processes to describe substrate utilization and population dynamics in biofilms. In the mid-80s, mathematical mixed culture multi-substrate one-dimensional biofilm models were developed by Kissel et al. (1984) and Wanner and Gujer (1986) to provide more accurate descriptions of system behaviors including the progression of biofilm thickness, microbial spatial distribution, and development in time of

dissolved and particulate components. The mixed culture model was modified according to new experimental findings and was implemented in the computer program AQUASIM equipped with the automatic parameter estimation and sensitivity analysis (Reichert, 1994).

The activated sludge model and the biofilm model were chosen and linked so that the IFAS model could be used for simultaneous simulation of carbonaceous organic removal, biological nitrogen removal, and biological phosphorus removal processes of the suspended solids and attached biofilm biomasses. Although the one-dimesional mixed-culture biofilm model can provide more accurate predictions of system behavior, it requires much greater computational effort for solving the necessary set of partial differential equations needed to express the complexity of the one-dimensional model. Therefore, the zero dimensional biofilm model was selected for this initial version of the IFAS computer model to provide quicker, but sufficiently accurate, simulations and predictions for IFAS design and operational management purposes. The models selected to develop the IFAS model in this paper are discussed further in the following sections.

Activated sludge Model

The general mechanistic model for biological nutrient removal (BNR) activated sludge systems proposed by Barker and Dold (1997) was chosen for modeling the suspended growth part of the IFAS model. This model was developed by combining ASM No.1 and the Wentzel Model (1989) so that the resulting model could be used to predict carbonaceous removal, nitrification, denitrification, and enhanced biological phosphorus removal (EBPR). Additionally, the kinetic and stoichiometric equations for the fermentation of readily biodegradable COD to short chain fatty acids and for anoxic and anaerobic hydrolysis were modified, and anoxic growth of biological phosphorus removal microorganisms was added. The model processes and descriptions were also presented in the same matrix format of the IAWQ models, ASM No. 1 and No. 2. The details of the model will not be discussed in this paper. The reader is referred to the previously referenced literature.

Biofilm Model

The zero-dimensional model, known as a fully penetrated biofilm model, was chosen for implementation of the attached growth segment of the IFAS model in this study. It is a simple kinetic biofilm model which disregards spatial gradients and structures within the biofilm. The substrate concentrations and active biomass volume fractions at the biofilm surface were assumed to be equal to their spatial average over the biofilm depth. It also assumes that the biofilm is homogeneous and the growth of biofilm is perpendicular to the surface of the film-water interface. Regardless, it provides reasonable approximations of biofilm thickness, the bulk substrate concentration, and substrate concentration and active biomass volume fractions inside the biofilm. It described the zero-dimensional model as a way to enable a very fast computation and still obtain sufficiently accurate results for substrate concentration profiles along the reactor or to describe biomass and substrate inputs and outputs for a mixed culture reactor, even though small errors may be introduced. If accuracy demands a one-dimensional biofilm model, the zero-dimensional model can be used as the initial solution of the differential system so that the computation time can be reduced by 50% or more (Gadani, 1993). Therefore, the zero-dimensional biofilm model is expected to provide fast computation and sufficiently accurate predictions for this version of an IFAS simulator.

The derivation of the zero-dimensional biofilm model is necessary so that the spatially-averaged values of active biomass, inert biomass, and substrate concentration in the biofilm can be obtained. The mass balance of active biomass is described by equation 1 which depends on the growth rate, decay rate, and the detachment rate of active biomass.

$$\frac{d}{dt}\left(\rho^i f^i(t)L(t)A\right) = \mu_f^i \rho^i f^i L(t)A - b^i \rho^i f^i(t)L(t)A + \delta(t)\rho^i f^i(t)A \qquad (1)$$

$$\text{and } \mu_f^i = \mu_{max,f}^i \frac{S_{s,f}(t)}{K_{s,f} + S_{s,f}(t)} \frac{S_{o,f}(t)}{K_{o,f} + S_{o,f}(t)} \qquad (1a)$$

where ρ^i, is the density of active biomass species i; A, the area of biofilm-water surface; b^i, the decay coefficient; $\mu_{max,f}^i$, the maximum specific growth rate of active biomass species i; f^i, fraction of active biomass species i; $S_{s,f}$, the substrate concentration in biofilm; $K_{s,f}$, the Monod coefficient for substrate; $S_{o,f}$, the electron acceptor in the biofilm; $K_{o,f}$, the Monod coefficient

for the electron acceptor(s) in the biofilm; L(t), the biofilm thickness; and $\delta(t)$,the detachment rate is described by Equation 2.

$$\delta(t) = -\lambda(L(t))^2 \tag{2}$$

where λ is the detachment rate coefficient.

Using the chain rule, equation 1 can be simplified to Equation 3 with the assumption that A and ρ^i are constant.

$$\frac{d(f^i(t))}{dt} = -\frac{f^i(t)}{L(t)}\frac{dL(t)}{dt} + \left(\mu_f^i - b^i\right)f^i(t) + \frac{\delta(t)f^i(t)}{L(t)} \tag{3}$$

The production of inert biomass also is calculated because some parts of bacteria are refractory to biodegradation. The mathematical expression is given by Equation 4 and 5.

$$\frac{d}{dt}\left(\bar{\rho}\bar{f}(t)L(t)A\right) = \left(\sum_{i=1}^{neps} b^i f_d \rho^i f^i(t)\right)L(t)A + \delta(t)\bar{\rho}\bar{f}A \tag{4}$$

$$\frac{d(\bar{f}(t))}{dt} = -\frac{\bar{f}(t)}{L(t)}\frac{dL(t)}{dt} + \sum_{i=1}^{neps}\left(\frac{b^i f_d \rho^i f^i(t)}{\bar{\rho}}\right) + \frac{\delta(t)\bar{f}}{L(t)} \tag{5}$$

where neps is the number of active biomass in the biofilm and f_d is the fraction of inert materials in biomass. $\bar{f}$ and $\bar{\rho}$ are the fraction of inert material and the density of inert materials, respectively.

The substrate concentration in the biofilm is expressed by Equation 6 and is dependent on the diffusion rate and the consumption rate.

$$\frac{d}{dt}\left(AS_f(t)L(t)\right) = A\frac{D}{L_L}(S_B(t) - S_f(t)) - \frac{\mu_f^i}{Y^i}L(t)\rho^i f^i(t)A \tag{6}$$

where the constants are D, the diffusivity; L_L, the thickness of laminar diffusion layer; Y^i, the yield coefficient; and $S_B(t)$, the substrate concentration in the bulk liquid. Again, the equations can be reduced to Equation 7 if A is assumed to be constant.

$$\frac{d(S_f(t))}{dt} = -\frac{S_f(t)}{L(t)}\frac{dL(t)}{dt} + \frac{D}{L_L}(S_B(t) - S_f(t)) - \frac{\mu_f^i}{Y^i}\rho^i f^i(t) \tag{7}$$

The thickness of the biofilm is governed by the net growth rates of all species including inert materials and the detachment rate. The rate of change in thickness is calculated by Equation 8.

$$\frac{dL(t)}{dt} = \frac{1}{1-\varepsilon_l}\left(\sum_{i=1}^{neps}\left(\mu^i - b^i(1-f_d)\right)f^i(t)L(t)\right) + \delta(t) \qquad (8)$$

where ε_l is the water content fraction in the biofilm

Interactions of Biofilm and Activated Sludge Model

The interactions of components in the bulk liquid and biofilm compartments of the IFAS process were depicted in Figure 1. It is necessary to group constituents in both compartments into particulate and dissolved components. Dissolved components are transported from the bulk liquid through a stagnant liquid film layer into the biofilm. Substrate concentrations in the biofilm are assumed to be continuous in time and space. Some substrates are transformed into new products by active biomass species and released to the bulk volume or utilized in the biofilm. The particulate components in the bulk liquid cannot be transferred into the biofilm, but attach to the biofilm surface by the 'attachment process'. Inversely, the biofilm can detach from the biofilm surface back to the bulk liquid in the 'detachment process'. The biofilm matrix consists of water in which the dissolved substances can be transported by molecular diffusion, active biomass species, and inert materials, all of which are expressed in terms of volume fractions. The sum of all fractions is equal to 1.0 in the biofilm matrix. The volume fraction of water and the density of solid materials are assumed to be constant and the attachment process is assumed to be negligible in this model.

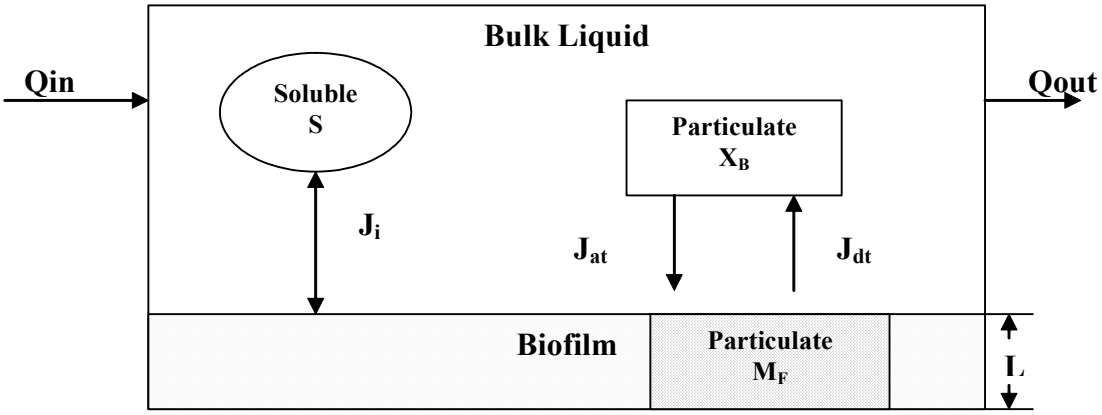

Figure 1 Interaction processes and components between biofilm and bulk liquid compartments

The mass balances for the active biomass and substrate in a continuous stirred tank reactor, k (CSTR), containing fixed biofilm attached to integrated media are described by Equations 9 and 10. Equation 9 represents the change in active biomass in the reactor, and is based on the growth and decay of suspended growth microorganisms and the detachment of biofilm. The biofilm is assumed to slough off from the surface of the biofilm and becomes part of the suspended biomass. It is assumed that the mixed liquor in the reactor is mixed homogenously; therefore, there is no spatial variableness in the reactor. Unlike the biofilm, the active biomass in the bulk liquid is expressed in concentration units. The change of substrate concentration in the reactor is the results of utilization by suspended growth and by biofilm as shown in Equation 10.

$$\frac{d(X_k^i(t))}{dt} = \frac{Q}{V}\left(X_{k-1}^i(t) - X_k^i(t)\right) + \left(\mu^i - b^i\right)X_k^i - \delta(t)\rho^i f^i \frac{A}{V} \tag{9}$$

$$\frac{d(S_k(t))}{dt} = \frac{Q}{V}(S_{k-1}(t) - S_k(t)) - \left(\frac{\mu_S}{Y^i}X_k^i\right) - \frac{D}{L_L}\left(S_k(t) - S_f(t)\right)\frac{A}{V} \tag{10}$$

The change in bulk liquid volume due to biofilm growth on the media typically is assumed to be negligible. However, the amount of media integrated into the reactor may be increased to provide sufficient specific surface area so that the effluent quality criteria can be met; hence the bulk liquid volume displaced by the media may be significant. Therefore, the knowledge of bulk liquid volume displacement by each media is required. Note that when sponge-like media is placed into liquid, it initially fills with water and the displacement of water is very small, however, during continuous flow operation, the water inside the sponges becomes stagnant, i.e., flow through does not occur, and the resulting decrease in the hydraulic retention time (HRT) is quite large.

Process Descriptions in Biofilm

The description of biological processes in the biofilm is presented in matrix format as shown in Tables 1&2. The bacteria growth rate was expressed as a double Monod-type reaction. The endogenous respiration and inactivation processes utilized by most biofilm models were replaced by the death-regeneration theory to make the biofilm model consistent with the general activated sludge model. To allow both consistent process description and wastewater characterization for the direct linkage between the biofilm model and the general model, readily biodegradable substrates were characterized as complex substrates and short chain fatty acid substrates. Slowly

biodegradable particulate organic substrates generated by the decay process were instantaneously hydrolyzed to readily biodegradable organic complex materials in this model. The processes consist of aerobic and anoxic heterotrophic growth and aerobic autotrophic growth. Excess phosphorus for biological growth and no EBPR processes in biofilm are assumed. All biomass components and inert residues are expressed in terms of volume fractions, and if they are multiplied by their densities the concentrations of biomass inert residues can be obtained.

Table 1 Rate expressions for the autotrophic/heterotrophic biofilm processes

$$R_1 = \mu_H \frac{SBSC}{K_{SH} + SBSC} \frac{O_2}{K_{OH} + O_2} \rho_H f_{ZBH}$$

$$R_2 = \mu_H \frac{SBSA}{K_{SH} + SBSA} \frac{O_2}{K_{OH} + O_2} \rho_H f_{ZBH}$$

$$R_3 = \eta_{GRO} \mu_H \frac{SBSC}{K_{SH} + SBSC} \frac{NO3 - N}{K_{NO} + NO3 - N} \frac{K_{OH}}{K_{OH} + O_2} \rho_H f_{ZBH}$$

$$R_4 = \eta_{GRO} \mu_H \frac{SBSA}{K_{SH} + SBSA} \frac{NO3 - N}{K_{NO} + NO3 - N} \frac{K_{OH}}{K_{OH} + O_2} \rho_H f_{ZBH}$$

$$R_5 = b_H \rho_H f_{ZBH}$$

$$R_6 = \mu_A \frac{NH4 - N}{K_{SN} + NH4 - N} \frac{O_2}{K_{OH} + O_2} \rho_A f_{ZBA}$$

$$R_7 = b_A \rho_A f_{ZBA}$$

where η_{GRO} is an anoxic growth factor. The rate expressions are numbered according the process numbers in Table 2. The state variables are listed as follows:

f_{ZBH} = volume fraction of heterotrophic bacteria

f_{ZBA} = volume fraction of autotrophic bacteria

f_{ZE} = volume fraction of inert material

SBSC = readily biodegradable complex substrates concentration

SBSA = readily biodegradable short chain fatty acids concentration

NO_3-N = nitrate concentration

NH_4-N = ammonium concentration

O_2 = oxygen concentration

Table 2 Matrix representation of process descriptions of aerobic/anoxic growth of heterotrophic and autotrophic bacteria in biofilm

R_j	Process	Biofilm Model							
		Biomass Fractions i			Substrate Compound i				
		f_{ZBH}	f_{ZBA}	f_{ZE}	SBSC	SBSA	NO_3-N	NH_4-N	O_2
1	Aerobic Heterotrophs Growth on SBSC	1.00			-1.00/Yhaer			$-f_{NZH}$	-(1.00-Yhaer)/Yhaer
2	Aerobic Heterotrophs Growth on SBSA	1.00				-1.00/Yhaer		$-f_{NZH}$	-(1.00-Yhaer)/Yhaer
3	Anoxic Heterotrophs Growth on SBSC	1.00			-1.00/Yhanx		-(1.00-Yhanx)/(2.86*Yhanx)	$-f_{NZH}$	
4	Anoxic Heterotrophs Growth on SBSA	1.00				-1.00/Yhanx	-(1.00-Yhanx)/(2.86*Yhanx)	$-f_{NZH}$	
5	Heterotrophs Decay	-1.00		fd	1-fd				
6	Aerobic Autotrophs Growth		1.00				1.00/YA	-1.00/YA-f_{NZA}	-(4.57-YA)/YA
7	Autotrophs Decay		-1.00	fd	1-fd				

where Yhaer, the yield coefficient for heterotrophs under aerobic conditions; Yhanx, the yield coefficient for heterotrophs under anoxic conditions; YA, the yield coefficient for autotrophs; f_{NZH} and f_{NZA}, nitrogen content of biomass; fd, the fraction of inert material in biomass.

Numerical Solution Techniques

The systems of ordinary differential equations from the zero-dimensional biofilm model and the general model for BNR activated sludge were solved simultaneously to find the dependent variables. If the steady state solutions are required, the globally convergent multi-dimensional Newton technique was used to find the roots of the systems of nonlinear equations of the suspended growth model and the zero-dimensional biofilm model. In contrast, when dynamic solutions are needed, the LSODA is employed to solve dynamically both systems of nonlinear equations for the suspended growth and attach growth systems. The LSODA numerical package is a solver for systems of ordinary differential equations with an automatic switching method for stiff and non-stiff problems. The two methods employed include Adams method with variable step size and variable order up to 12th order for non-stiff problems and Gear (or BDF) method with variable step size and variable order up to 5th order for stiff equations. It is, therefore, very convenient for users since they do not have to determine whether the problem is stiff or not. The solver will automatically choose the appropriate method, but always starts with the non-stiff method (Petzold, 1983).

MODEL IMPLEMENTATION

To obtain flexibility in implementing the IFAS model developed in this study and to keep it independent of commercial generic simulators, Borland C++ Builder package (a C++ compiler) was used to develop an IFAS simulator program which was written for Windows-based personal computers. The software was designed as a 32 bit application and compiled on a Windows 2000 based personal computer, but it should be compatible with any Windows 95/98/NT/2000/ME/XP systems. The program incorporates many utilities and functions including graphical plotting and report generation functions to provide users with user-friendly and interactive software. Two core numerical libraries, which were taken from Numerical Recipes and LSODA numerical library to find the root of a system of nonlinear equations and to solve a system of ordinary differential equations, were used as numerical solvers in the IFAS simulator. This simulator allows users to design and simulate conventional activated sludge systems, two to five stage biological nutrient removal (BNR) systems, and BNR systems that include IFAS modifications, i.e., with media in either or both of the anoxic and anaerobic zones. The toggle between IFAS and conventional BNR processes is the amount of media installed in the system. The amount of

media will be added in terms of reactor volume fraction; therefore, the volume of each media unit is required. The total media volume in each reactor will be calculated according to the fraction that users enter. After knowing the number of media units installed, the volume of liquid displaced by media will be calculated and used to adjust the bulk liquid volume. The IFAS simulator asks users for the inputs such as system configurations, operating conditions, kinetic and stoichiometric parameters. The IFAS simulation begins with the calculation of net bulk liquid volume by subtracting with the volume of liquid displaced by installed media materials. The wastage flow is then calculated according to the specified operating mixed liquor suspended solids (MLSS) solid retention time (SRT) or specified wastage flows from each reactor. With specified simulation parameters such as temperature, SRT, kinetic and stoichiometric parameters, amount of installed media, and system configuration, the suspended growth processes without interactions from the fixed film media are simulated and then followed by the simulation of the biofilm model alone. With predicted dependent variables from the previous simulation, the simulation starts again with interactions from the fixed film on the media using those values as initial values.

MODEL EVALUATION

Modeling is generally implemented at either dynamic or steady state conditions. However, only results from the steady state simulation with given sets of conditions are unique because all quantities are assumed to be constant with time. Additionally, dynamic simulations will tend toward the steady state solution; therefore, with the steady state solution available, in most cases the time required to initialize the dynamic simulation will be considerably shortened. Therefore, only steady state simulations were conducted for the model evaluation in this paper.

The experimental data from pilot plant studies with Captor® or Accuweb® as integrated fixed film media in three stage UCT/VIP BNR systems were used to evaluate the accuracy of the model. In the IFAS-Captor® studies, two pilot-scale systems were conducted on the campus of Virginia Tech, Blacksburg, VA (Sen, 1995) using settled municipal wastewater supplemented with chemicals to enhance the strength of the sewage. Each system consists of two anaerobic, two anoxic, and three aerobic reactors, and one clarifier as illustrated by Figure 2. Each train also had a small reactor for deoxygenation of the recycles from the last aerobic reactor and the

return activated sludge (RAS) from the bottom of the clarifier. One of the three systems was operated as a Control system and contained no media. One of the systems had Captor® media installed in all three aerobic reactors at 30% of reactor volume. Sewage was pumped each day and kept equilibrated in the 12 ^{o}C temperature for 24 hours. After the chemicals were added, the sewage was pumped with the flow rate of 207 L/day to each system; therefore, nominal HRT was 12 hours. Aerobic SRT was used as a key operating parameter and varied between 0.33 to 3.1 days.

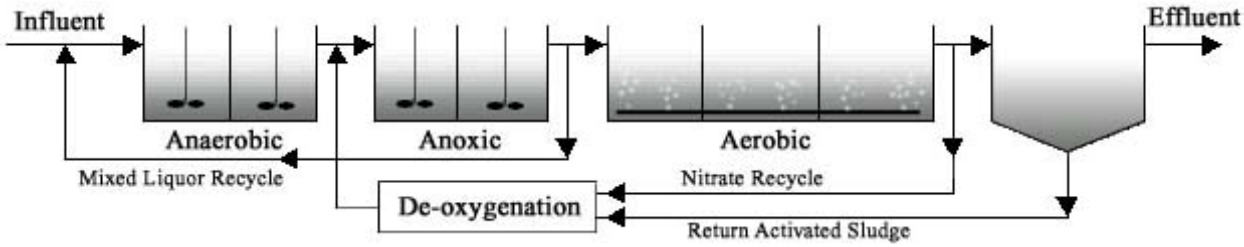

Figure 2: Schematic of UCT/VIP configuration systems used as the base system during the experiments

The strength of the municipal wastewater with supplemental sodium acetate, urea, and phosphorus was 450-550 mg/L COD, 55-65 mg/L TKN, and above 3 mg/L TP, respectively. A media fill volume fraction of 30 percent with a volume of 8 cm^3 and a specific surface area of 25 cm^2 each Captor® sponge was added to each aerobic tank. The Captor® media consists of polyurethane foam cubes with dimensions of 25.4 mm. x 25.4 mm. x 12.5 mm. and a porosity of 97%. Biofilm growth on the media was determined to have a volatile suspended solids (VSS) fraction of 90 percent with an average density of 32 mg VSS/cm^3 (as observed in aerobic cell No. 2) (Sen, 1995).

Similar studies using Accuweb® media with emphasis on enhanced denitrification and EBPR in the IFAS systems were also conducted at Virginia Tech (Sriwiriyarat and Randall, 2002a & b). Two IFAS systems with the same configuration as shown in Figure 2 but with different media racks and reactor locations were operated in parallel with a conventional three stage BNR system

treated as a control. The systems were fed 175 L/d of municipal sewage that had been supplemented with sodium acetate, urea, and potassium dihydrogenphosphate to increase the strength. The operating conditions were 10 and 6 days SRT under a temperature of 10 ^{o}C. The COD/TP ratios were 18 at 10 days SRT and 20 and 52 at 6 days SRT. The Accuweb® media was installed in the anoxic zones and aerobic zones in two IFAS systems. The locations of media in the aerobic zones of IFAS processes were varied depending on the phases of the experiments. More details of these studies are available in the publications of Sriwiriyarat (2002), and Sriwiriyarat and Randall (2002a & b).

The experimental data from the IFAS-Captor® studies at 0.33 to 3.1 day aerobic SRTs were used to calibrate the IFAS model using empirical equations (Sriwiriyarat, 1999). The experimental data from the IFAS-Captor® system operated at 3.1 days aerobic SRT, and the IFAS-Accuweb® operated at 6 days SRT and COD/TP ratio of 20, plus from the control systems operated in parallel, were used to evaluate the IFAS model developed in this article. The aerobic SRT from the IFAS-Captor® studies was converted to the total SRT for simulation purposes. A few parameters related to EBPR were adjusted for evaluation of the IFAS-Accuweb® processes with the IFAS model.

Most stoichiometric and kinetic parameters for the general model and the biofilm model were taken from the literature and will not be listed in this paper (Barker and Dold, 1997; Sen, 1995). Only the parameters that were changed in the studies are summarized in Tables 3, 4, 5, and 6. Even though the pilot-scale systems were operated at 10 ^{o}C and 12 ^{o}C, the kinetic and other rate parameters were adjusted to 20 ^{o}C before listing to generalize the model, with the exception of the diffusion coefficients, and no conversion factors were available for them (Sen, 1995). The λ coefficient value was chosen arbitrarily so that the predicted biofilm thickness was close to the experimental observations. The λ value was set at a very small number in the simulator because it was assumed that very little biomass detached to the bulk liquid due to growth in the pore spaces of the sponge media. After IFAS-Captor® simulation, the λ value was kept at the same value for the IFAS-Accuweb® simulation. In addition, the water content in the biofilm (ε_l) was assumed to be zero for the model evaluations.

The simulations were performed using a personal computer with 733 MHz processor speed and 832 megabytes of memory. The computation time for UCT/VIP with integrated Captor® was 26 minutes at 3.1 days aerobic SRT with 475 iterations and at a tolerance of $1.0x10^{-4}$. With the availability of current technologies, the computation time can be reduced if a higher capacity computer is used to perform the simulation.

The IFAS simulation results using the zero-dimensional mechanistic biofilm model were compared to the predictions from the IFAS model using empirical equations determined by batch studies and experimental data to demonstrate the accuracy of the model. To demonstrate the capacity of the new IFAS model for simulating conventional BNR-AS systems, simulations were compared to the experimental results from the control systems operated in parallel with the Captor® and Accuweb® IFAS systems. Abbreviation terms used in this paper are:

- IFAS 1 which is the previous version of IFAS model that uses empirical equations to predict substrate flux in the biofilm.
- IFAS 2 which is the IFAS model that uses the zero-dimensional biofilm model.
- IFAS-Captor and IFAS-Accuweb are IFAS systems with integrated Captor® and Accuweb® media, respectively.
- Control-Captor and Control-Accuweb are the Control systems operated in parallel with the IFAS-Captor and IFAS-Accuweb systems.

As shown in Figures 3 and 4, the IFAS 2 model predicts the best fit for soluble organic substrates expressed in terms of COD for both IFAS and conventional BNR systems. The parameters calibrated with IFAS 1 and experimental results from the IFAS-Captor studies provided excellent predictions of substrate profiles when compared with experimental results from the IFAS-Accuweb systems.

The IFAS 2 model could be used to replace the IFAS 1 model which used empirical equations for biological nitrogen removal for both IFAS and Control systems as illustrated in Figures 4 and 5. IFAS 2 provided the same or slightly better nitrate profiles than IFAS 1. When the parameters calibrated with experimental results from the IFAS Captor® system were used to

simulate the IFAS Accuweb® system, the IFAS 2 model still provided good predictions for nitrate and ammonium profiles in the aerobic zones. The predicted ammonium concentrations in the anaerobic zones of the IFAS-Accuweb and Control-Accuweb systems were higher than the experimental concentrations. It is possible that the wastewater characteristics during the experiments were different and that the hydrolysis parameters for organic nitrogen and ammonification need to be adjusted when they are applied to the IFAS-Accuweb system.

Table 3 Stoichiometric parameters for suspended growth in the general model used for the IFAS model evaluations

Symbol	Characterization	Value	Units
Non-polyP Heterotrophs			
Yhaer	Aerobic yield	0.582	mg cell COD yield (mg COD utilized)$^{-1}$
Yhanx	Anoxic yield	0.440	mg cell COD yield (mg COD utilized)$^{-1}$
Yhana	Anaerobic yield	0.440	mg cell COD yield (mg COD utilized)$^{-1}$
Yac	Fermentation Sbsa yield	0.700	mg Sbsa COD (mg Sbsc COD)$^{-1}$
Eanox	Anoxic hydrolysis efficiency factor	0.700	mg Sbsc COD (mg Senm COD)$^{-1}$
Eana	Anaerobic hydrolysis efficiency factor	0.500	mg Sbsc COD (mg Senm COD)-1
Fnzh	Nitrogen content of active mass	0.085	mg N (mg COD active organisms)$^{-1}$
Fnzeh	Nitrogen content of endogenous mass	0.085	mg N (mg COD endogenous residue)-1
Fcvh	COD:VSS ratio	1.420	mg COD (mg VSS)$^{-1}$
Autotrophs			
Ya	Yield	0.142	mg cell COD yield (mg N utilized)$^{-1}$
Fnza	Nitrogen content of active mass	0.085	mg N (mg COD active organisms)$^{-1}$
Fnzea	Nitrogen content of endogenous mass	0.085	mg N (mg COD endogenous residue)-1
Fcva	COD:VSS ratio	1.420	mg COD (mg VSS)$^{-1}$
PolyP Heterotrophs			
Yp	Yield	0.582	mg cell COD yield (mg COD utilized)$^{-1}$
Fp,upt	P uptake/COD utilized in aerobic growth	0.820	mg P/ (mg stored COD)

Table 4 Kinetic parameter values for suspended growth in the general model at 20 ^{o}C in IFAS model evaluation

Symbol	Characterization	Value	Units	θ_T
Non-polyP Heterotrophs				
μ_H	Maximum specific growth rate	6.423	d^{-1}	1.030
$K_{SH,}$	Half saturation coefficient	61	mg COD l^{-1}	1.030
b_H	Decay rate	0.064	d^{-1}	1.055
η_{GRO}	Anoxic growth factor	0.496		
K_H	Maximum specific hydrolysis rate	4.450	d^{-1}	1.050
Autotrophs				
μ_A	Maximum specific growth rate	0.545	d^{-1}	1.030
K_{NH}	Half saturation coefficient	1.495	mg N l^{-1}	1.060
b_A	Decay rate	0.035	d^{-1}	1.060

Table 5 Stoichiometric and kinetic parameter values of the biofilm @ 20 oC

	Heterotrophs	Autotrophs	Inert Biomass
Maximum growth rate	3.68 day^{-1}	0.62 day^{-1}	
Biomass Yield	0.45	0.07	
Organism decay rate	0.067 day^{-1}	0.037 day^{-1}	
Substrate half saturation coefficient	60.38 mg COD/L	2 mg COD/L	
Oxygen half saturation coefficient	0.86 mg DO/L	2 mg DO/L	
Nitrate half saturation coefficient	1.73 mg N/L		
Anoxic growth factor (nGro)	0.184		
Biomass Density	45.44 mg/cm^3	45.44 mg/cm^3	45.44 mg/cm^3

Table 6 Substrate diffusion coefficients and conversion factors.

Substrate diffusion coefficients D within the biofilm at 12 ^{o}C		
Readily biodegradable complex substrates	0.654	cm^2/d
Readily biodegradable SCFA substrate	0.654	cm^2/d
Nitrate nitrogen	0.840	cm^2/d
Ammonium nitrogen	0.720	cm^2/d
Oxygen	1.138	cm^2/d
Conversion factors		
Nitrogen content in biomass (f_{NZH}, f_{NZA})	0.085	g N/g COD
Fraction of inert material in biomass	0.080	

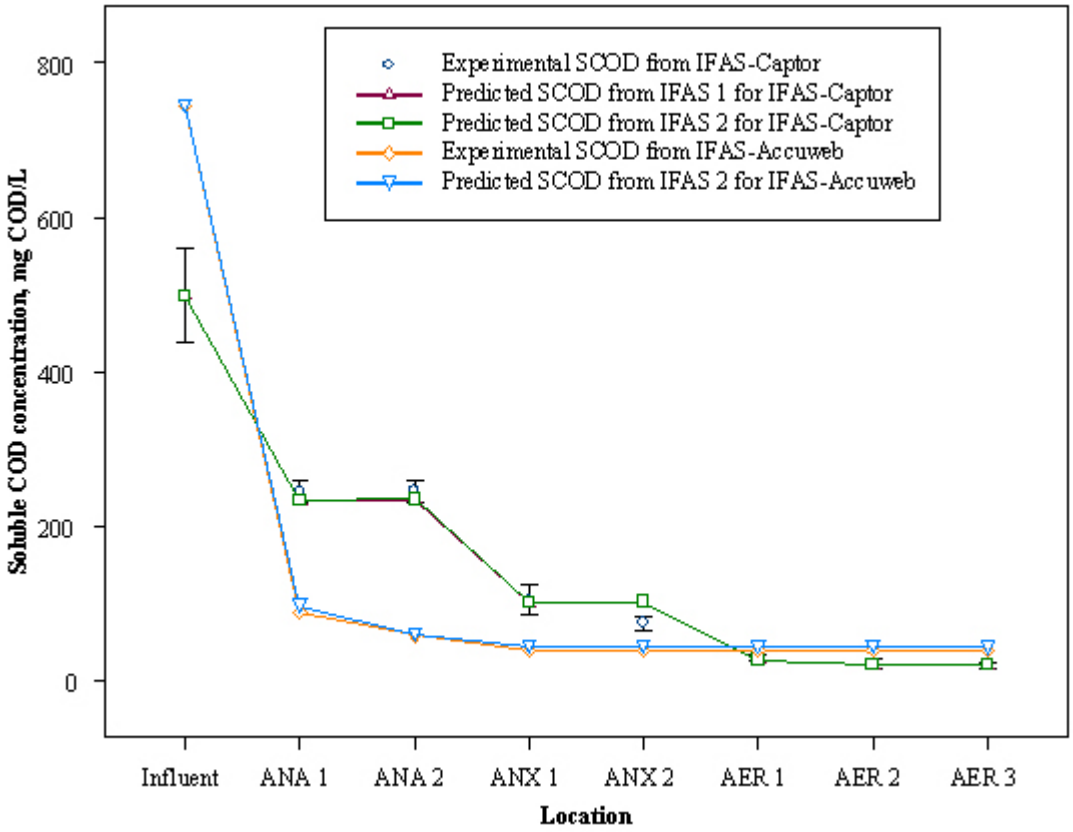

Figure 3: The comparisons between the experimental results and predicted values from IFAS 1 and IFAS 2 for soluble COD concentrations in the IFAS systems integrated with Captor® and Accuweb® media.

Figures 7 and 8 illustrate the improvement of IFAS 2 over IFAS 1 for the prediction of volatile suspended solids concentrations. However, when IFAS 2 was applied without adjusting

parameters, the IFAS 2 simulation results did not quite fit the experimental values determined for both the IFAS and Control systems.

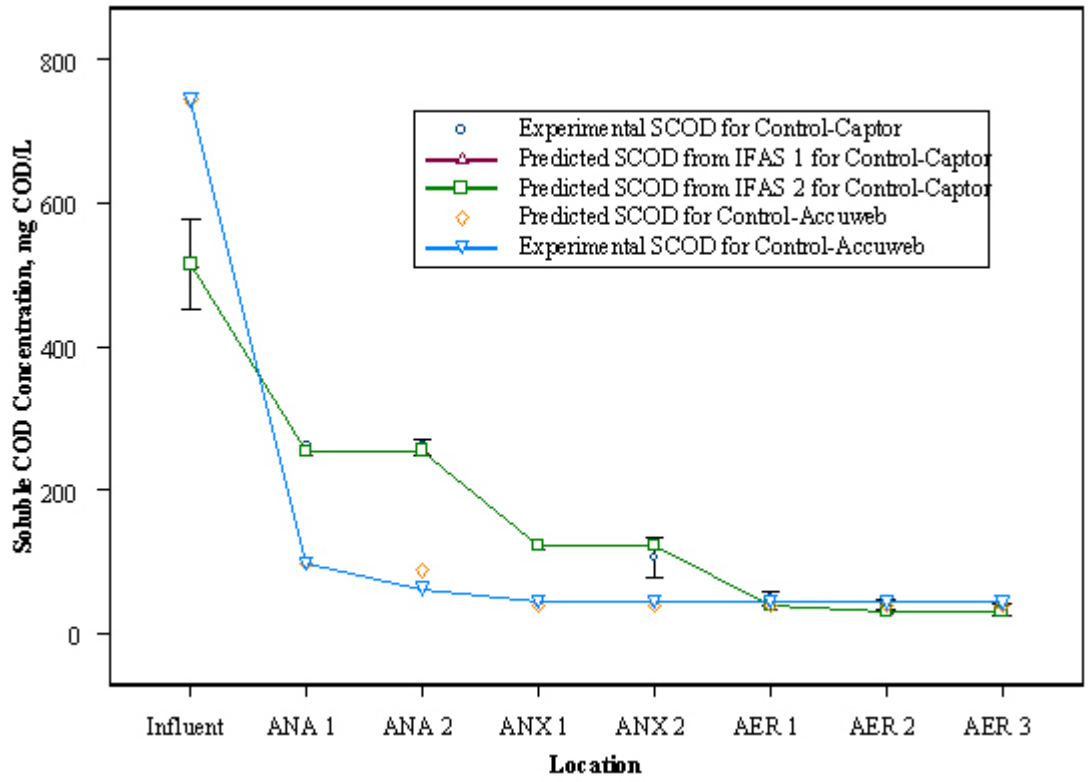

Figure 4: Comparisons between the experimental results and predicted values from IFAS 1 and IFAS 2 for soluble COD concentrations in the Control systems operated without media installed.

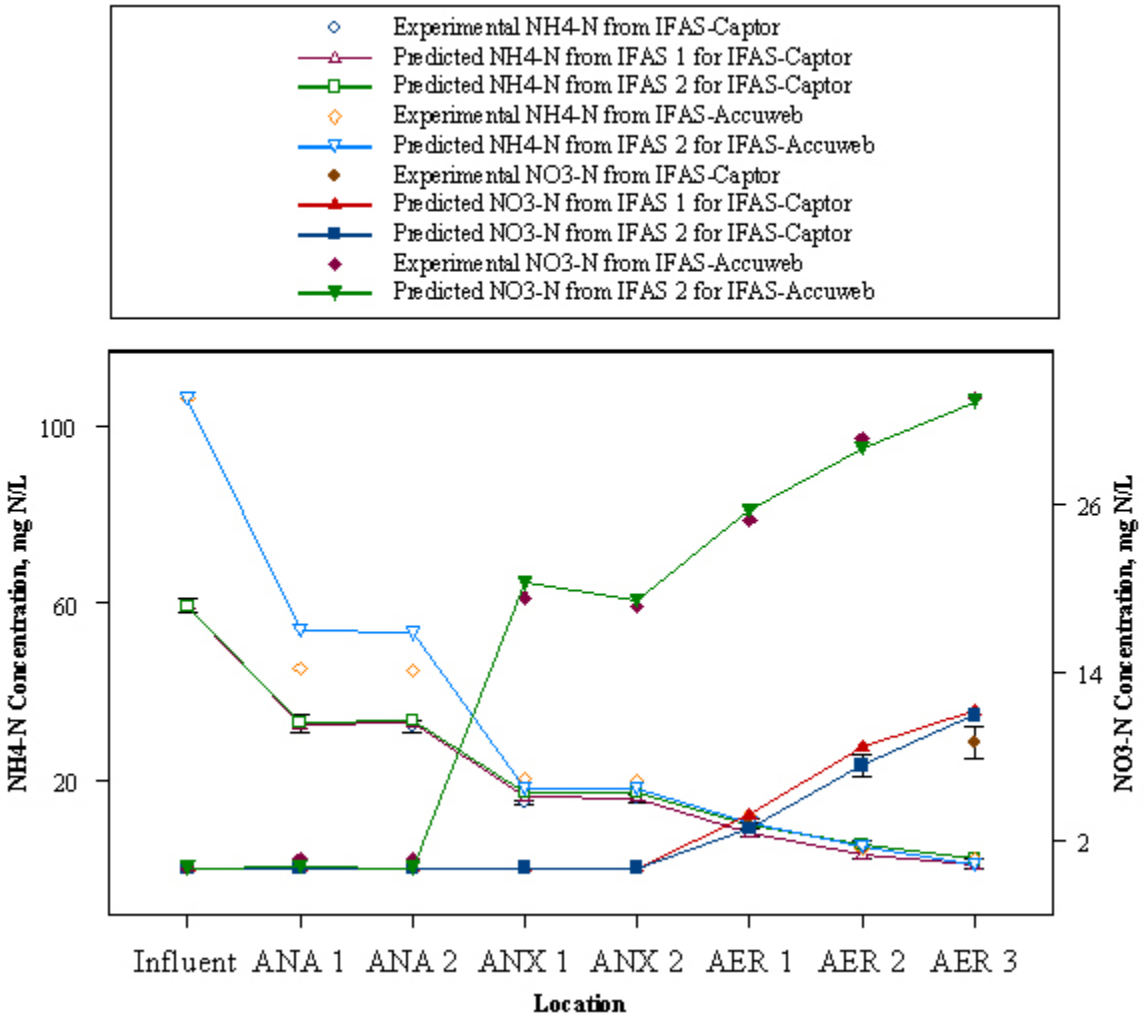

Figure 5: Comparisons between the experimental results and predicted values from IFAS 1 and IFAS 2 for ammonium and nitrate concentrations in the IFAS systems integrated with Captor® and Accuweb® media.

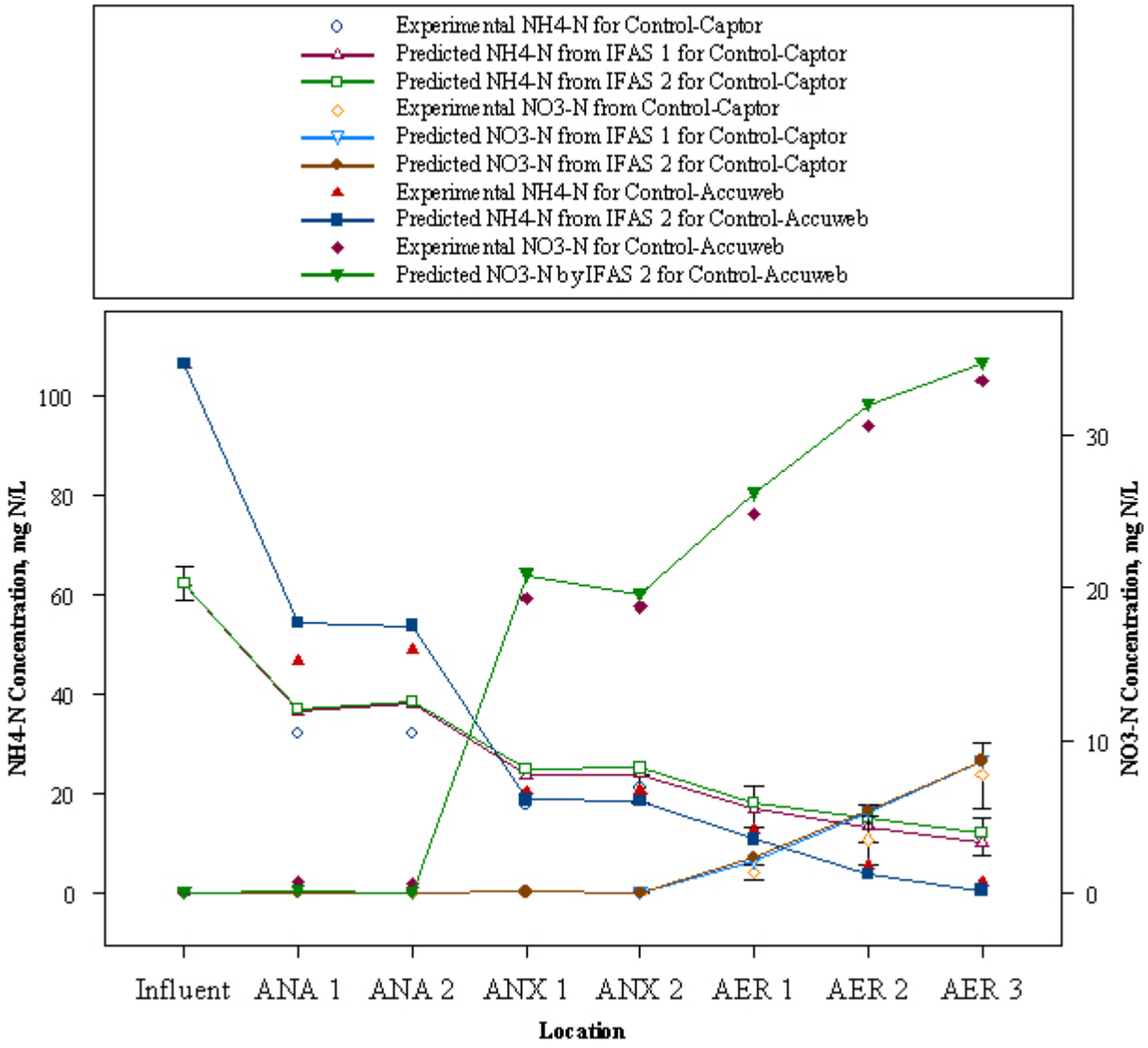

Figure 6: Comparisons between the experimental results and predicted values from IFAS 1 and IFAS 2 for ammonium and nitrate concentrations in the Control systems (no media).

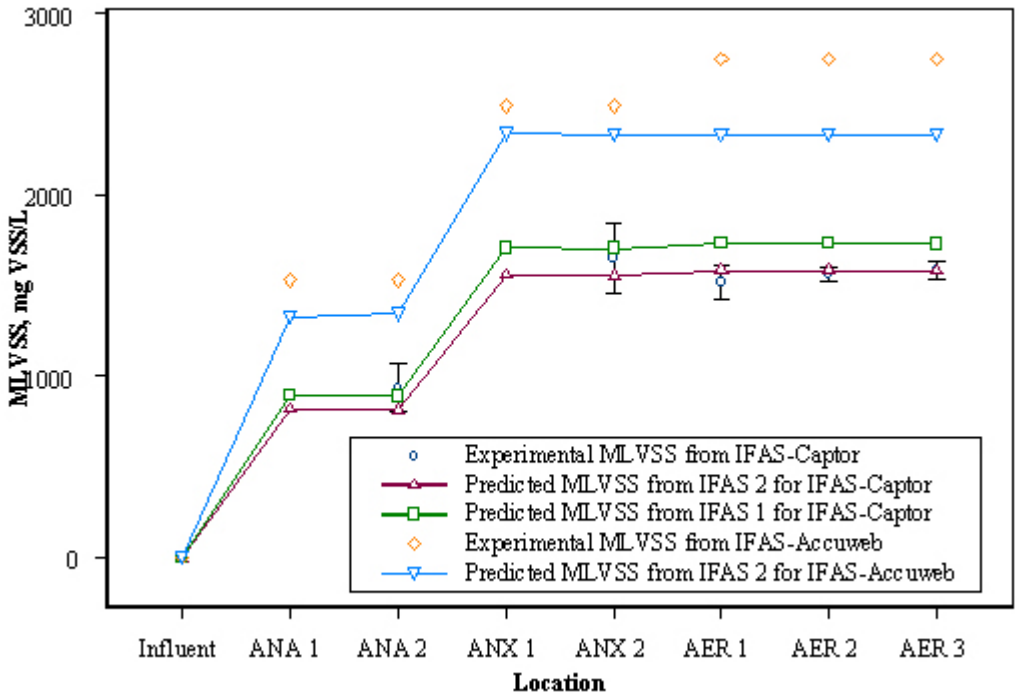

Figure 7: Comparisons between the experimental and predicted values from IFAS 1 and IFAS 2 for MLVSS concentrations in the IFAS systems.

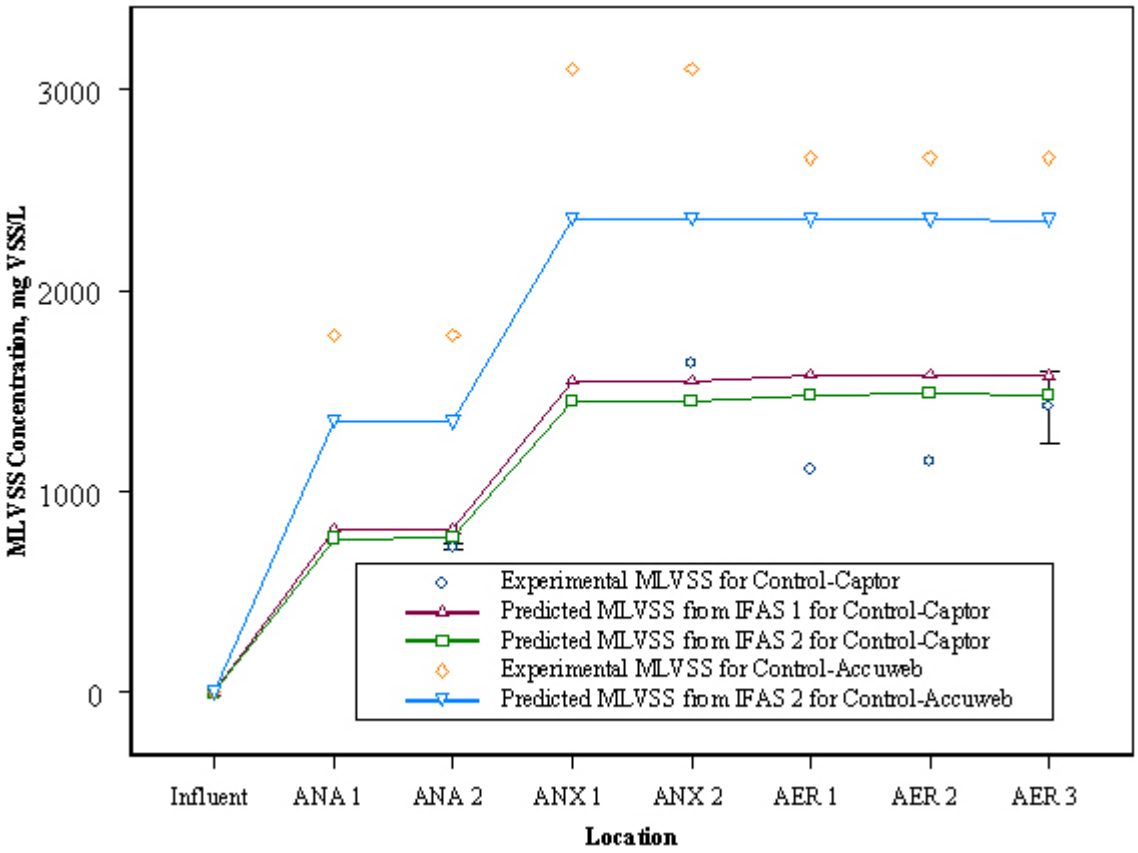

Figure 8: Comparisons between the experimental results and predicted values from IFAS 1 and IFAS 2 for MLVSS concentrations in the Control systems (no media).

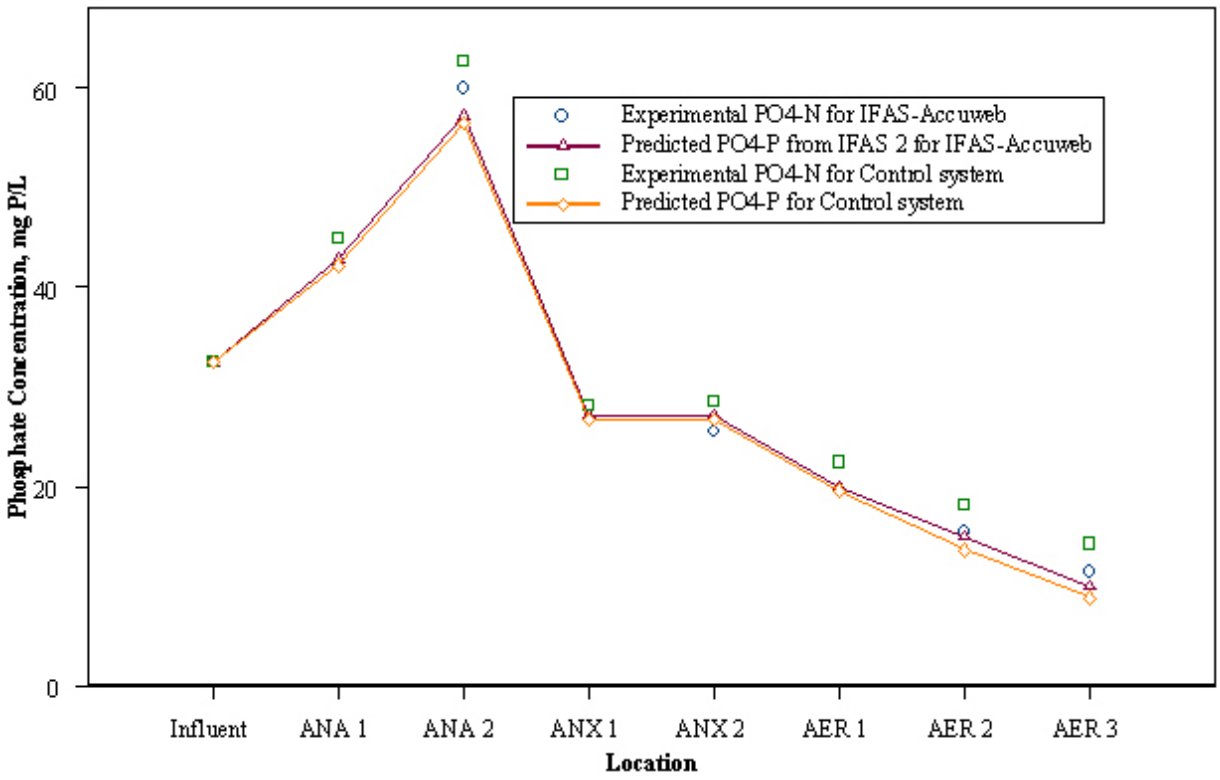

Figure 9: Phosphate profiles predicted by IFAS 2 compared with experimental data from both the IFAS-Accuweb and Control systems.

The phosphorus profiles presented in Figure 9 were predicted by IFAS 2 using adjusted EBPR parameters as listed in Table 3. They fit well with the measured phosphorus concentrations. However, the total phosphorus released and the aerobic phosphorus uptake were under predicted as compared to the experimental data from the Control-Accuweb system. The simulations were not compared with the IFAS 1 model and experimental data from the IFAS-Captor experiments because the IFAS-Captor system did not accomplish EBPR.

SUMMARY AND CONCLUSIONS

The IFAS model constructed using an interacting combination of the general model for biological nutrient removal and the mechanistic zero-dimensional biofilm model provided the same accuracy as the IFAS model developed using empirical equations. The model was calibrated and evaluated using parameters from the empirical IFAS model and experimental data from the IFAS systems separately integrated with Captor® and Accuweb® media. The

simulations results showed that the IFAS model developed during this study can be used to replace the empirical equations IFAS model. The sets of parameters from one IFAS system can be used to accurately predict both carbonaceous and nitrogen removal in the other IFAS system, i.e., integrated with another type of media. A few adjustments of the EBPR parameters were needed to accurately predict EBPR. The EBPR results from the simulations provided a reasonable fit with the experimental data, but further calibration of the EBPR parameters is needed.

The mechanistic nature of the new IFAS model enables its application for any type of media and it can be applied for different system designs and operating conditions. The interactions between two suspended growth and fixed film components are the key part of this IFAS model. Utilization of the zero-dimensional biofilm model reduced the computational efforts needed to simulate fixed film behavior by ignoring the changes in the biofilm. However, it still provided good estimation of biomass and substrate concentrations that entered and left the mixed culture reactors. If more predictive accuracy and knowledge of the microbial distribution and substrate profiles inside biofilm are desired, the zero-dimensional model could be replaced by the one-dimensional biofilm model as the core biofilm model. However, the results indicate that the zero-dimensional biofilm model would be a good tool for generating the initial values for the one-dimensional biofilm model because it provides reasonably accurate estimates of biofilm behavior under the given conditions. For the IFAS simulator, its utilization provides a user-friendly, interactive computer model for the design and operation of IFAS processes. Nonetheless, plans are underway to further develop the model by including the one-dimensional biofilm model. Further, additional calibration and verification are planned to incorporate the integration of fixed film media in the anoxic zone into the model.

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APPENDIX A:

Statistical Analysis

T-Test Report for Experiment Phase I

Variable: **Denitrification**

Descriptive Statistics Section:

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	3	6.53	1.33	0.77	3.23	9.83
Pilot system=IFAS1	3	6.62	0.76	0.44	4.75	8.50

Note: T-alpha (Pilot system=Control) = 4.30, T-alpha (Pilot system=IFAS1) = 4.30

Confidence-Limits of Difference Section:

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	4	-9.33E-02	1.08	0.88	-2.54	2.36

Note: T-alpha (Equal) = 2.7764

Equal-Variance T-Test Section:

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	-0.11	0.92	Accept Ho	0.05	0.01
Difference < 0	-0.11	0.46	Accept Ho	0.06	0.01
Difference > 0	-0.11	0.54	Accept Ho	0.04	0.01

Difference: (Pilot system=Control)-(Pilot system=IFAS1)

Descriptive Statistics Section:

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	3	6.53	1.33	0.77	3.23	9.83
Pilot system=IFAS2	3	6.37	1.24	0.72	3.28	9.46

Note: T-alpha (Pilot system=Control) = 4.30, T-alpha (Pilot system=IFAS2) = 4.30

Confidence-Limits of Difference Section:

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	4	0.16	1.29	1.05	-2.76	3.07

Note: T-alpha (Equal) = 2.7764

Equal-Variance T-Test Section:

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	0.15	0.89	Accept Ho	0.05	0.01
Difference < 0	0.15	0.56	Accept Ho	0.04	0.01
Difference > 0	0.15	0.44	Accept Ho	0.06	0.01

Difference: (Pilot system=Control)-(Pilot system=IFAS2)

Variable: **Nitrification**

Descriptive Statistics Section:

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	3	9.50	1.82	1.05	4.99	14.01
Pilot system=IFAS1	3	9.44	1.22	0.70	6.41	12.46

Note: T-alpha (Pilot system=Control) = 4.30, T-alpha (Pilot system=IFAS1) = 4.30

Confidence-Limits of Difference Section:

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	4	0.06	1.55	1.26	-3.45	3.57

Note: T-alpha (Equal) = 2.7764

Equal-Variance T-Test Section:

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	0.05	0.96	Accept Ho	0.05	0.01
Difference < 0	0.05	0.52	Accept Ho	0.05	0.01
Difference > 0	0.05	0.48	Accept Ho	0.05	0.01

Difference: (Pilot system=Control)-(Pilot system=IFAS1)

Descriptive Statistics Section:

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	3	9.50	1.82	1.05	4.99	14.00
Pilot system=IFAS2	3	9.25	1.76	1.02	4.87	13.63

Note: T-alpha (Pilot system=Control) = 4.30, T-alpha (Pilot system=IFAS2) = 4.30

Confidence-Limits of Difference Section:

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	4	0.25	1.79	1.46	-3.81	4.30

Note: T-alpha (Equal) = 2.7764

Equal-Variance T-Test Section:

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	0.17	0.87	Accept Ho	0.05	0.01
Difference < 0	0.17	0.56	Accept Ho	0.04	0.01
Difference > 0	0.17	0.44	Accept Ho	0.07	0.01

Difference: (Pilot system=Control)-(Pilot system=IFAS2)

Variable: **Net P Uptake**

Descriptive Statistics Section:

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	4	23.85	2.87	1.44	19.28	28.42
Pilot system=IFAS1	4	20.95	2.69	1.35	16.66	25.24

Note: T-alpha (Pilot system=Control) = 3.18, T-alpha (Pilot system=IFAS1) = 3.18

Confidence-Limits of Difference Section

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	6	2.9	2.79	1.97	-1.92	7.72

Note: T-alpha (Equal) = 2.4469

Equal-Variance T-Test Section

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	1.47	0.19	Accept Ho	0.24	0.07
Difference < 0	1.47	0.90	Accept Ho	0.0015	0.00
Difference > 0	1.47	0.10	Accept Ho	0.37	0.12

Difference: (Pilot system=Control)-(Pilot system=IFAS1)

Descriptive Statistics Section

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	4	23.85	2.87	1.44	19.28	28.42
Pilot system=IFAS2	4	23.68	3.44	1.72	18.20	29.15

Note: T-alpha (Pilot system=Control) = 3.18, T-alpha (Pilot system=IFAS2) = 3.18

Confidence-Limits of Difference Section

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	6	0.18	3.17	2.24	-5.31	5.66

Note: T-alpha (Equal) = 2.4469

Equal-Variance T-Test Section

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	0.08	0.94	Accept Ho	0.05	0.01
Difference < 0	0.08	0.53	Accept Ho	0.04	0.01
Difference > 0	0.08	0.47	Accept Ho	0.06	0.01

Difference: (Pilot system=Control)-(Pilot system=IFAS2)

Variable **Effluent Phosphorus**

Descriptive Statistics Section

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	4	9.975	1.466004	0.7330018	7.642261	12.30774
Pilot system=IFAS1	4	12.875	1.463728	0.731864	10.54588	15.20412

Note: T-alpha (Pilot system=Control) = 3.1824, T-alpha (Pilot system=IFAS1) = 3.1824

Confidence-Limits of Difference Section

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	6	-2.9	1.464866	1.035817	-5.434553	-0.3654473
Unequal	6.00	-2.9	2.071634	1.035817	-5.434554	-0.3654459

Note: T-alpha (Equal) = 2.4469, T-alpha (Unequal) = 2.4469

Equal-Variance T-Test Section

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	-2.7997	0.031175	Reject Ho	0.648219	0.305899
Difference < 0	-2.7997	0.015588	Reject Ho	0.794516	0.442136
Difference > 0	-2.7997	0.984412	Accept Ho	0.000014	0.000002

Difference: (Pilot system=Control)-(Pilot system=IFAS1)

Descriptive Statistics Section

Variable	Count	Mean	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Pilot system=Control	4	9.975	1.466004	0.7330018	7.642261	12.30774
Pilot system=IFAS2	4	10.15	3.031501	1.515751	5.326205	14.97379

Note: T-alpha (Pilot system=Control) = 3.1824, T-alpha (Pilot system=IFAS2) = 3.1824

Confidence-Limits of Difference Section

Variance Assumption	DF	Mean Difference	Standard Deviation	Standard Error	95% LCL of Mean	95% UCL of Mean
Equal	6	-0.175	2.381089	1.683684	-4.294826	3.944826
Unequal	4.33	-0.175	3.367368	1.683684	-4.7123	4.3623

Note: T-alpha (Equal) = 2.4469, T-alpha (Unequal) = 2.6949

Equal-Variance T-Test Section

Alternative Hypothesis	T-Value	Prob Level	Decision (5%)	Power (Alpha=.05)	Power (Alpha=.01)
Difference <> 0	-0.1039	0.920605	Accept Ho	0.050898	0.010238
Difference < 0	-0.1039	0.460303	Accept Ho	0.060337	0.012465
Difference > 0	-0.1039	0.539697	Accept Ho	0.041118	0.007967

Difference: (Pilot system=Control)-(Pilot system=IFAS2)

Analysis of Variance Report for Experiments Phase II and III

Response:Net P Uptake
Hypothesis:

H_O = There is no effect of COD/TP ratio on the mean net phosphorus uptake
H_A = There is an effect of COD/TP ratio on the mean net phosphorus uptake

H_O = There is no difference in mean net phosphorus uptake between pilot systems
H_A = There is difference in mean net phosphorus uptake between pilot systems

H_O = There is no interaction of COD/TP ratio and pilot systems on the mean net phosphorus uptake
H_A = There is interaction of COD/TP ratio and pilot systems on the mean net phosphorus uptake

Expected Mean Squares Section:

Source Term	DF	Term Fixed?	Denominator Term	Expected Mean Square
A: COD/TP	1	Yes	S	S+bsA
B: Pilot System	2	Yes	S	S+asB
AB	2	Yes	S	S+sAB
S	18	No		S

Note: Expected Mean Squares are for the balanced cell-frequency case.

Analysis of Variance Table:

Source Term	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power (Alpha=0.05)
A: COD/TP Ratio	1	1941.48	1941.48	391.75	0.00*	1.00
B: Pilot system	2	4.11	2.06	0.42	0.67	0.11
AB	2	0.54	0.27	0.05	0.95	0.06
S	18	89.21	4.96			
Total (Adjusted)	23	2035.33				
Total	24					

* Term significant at alpha = 0.05

Means and Effects Section:

Term	Count	Mean	Standard Error	Effect
All	24	12.07		12.07
A: COD/TP Ratio				
20	12	21.06	0.64	8.99
52	12	3.07	0.64	-8.99
B: Pilot system				
Control	8	12.55	0.79	0.48
IFAS 1	8	11.54	0.79	-0.53
IFAS 2	8	12.12	0.79	0.05
AB: COD/TP Ratio,Pilot system				
20,Control	4	21.61	1.11	7.21E-02
20,IFAS 1	4	20.32	1.11	-0.21
20,IFAS 2	4	21.25	1.11	0.14
52,Control	4	3.48	1.11	-7.21E-02
52,IFAS 1	4	2.75	1.11	0.21
52,IFAS 2	4	2.99	1.11	-0.14

Plots Section:

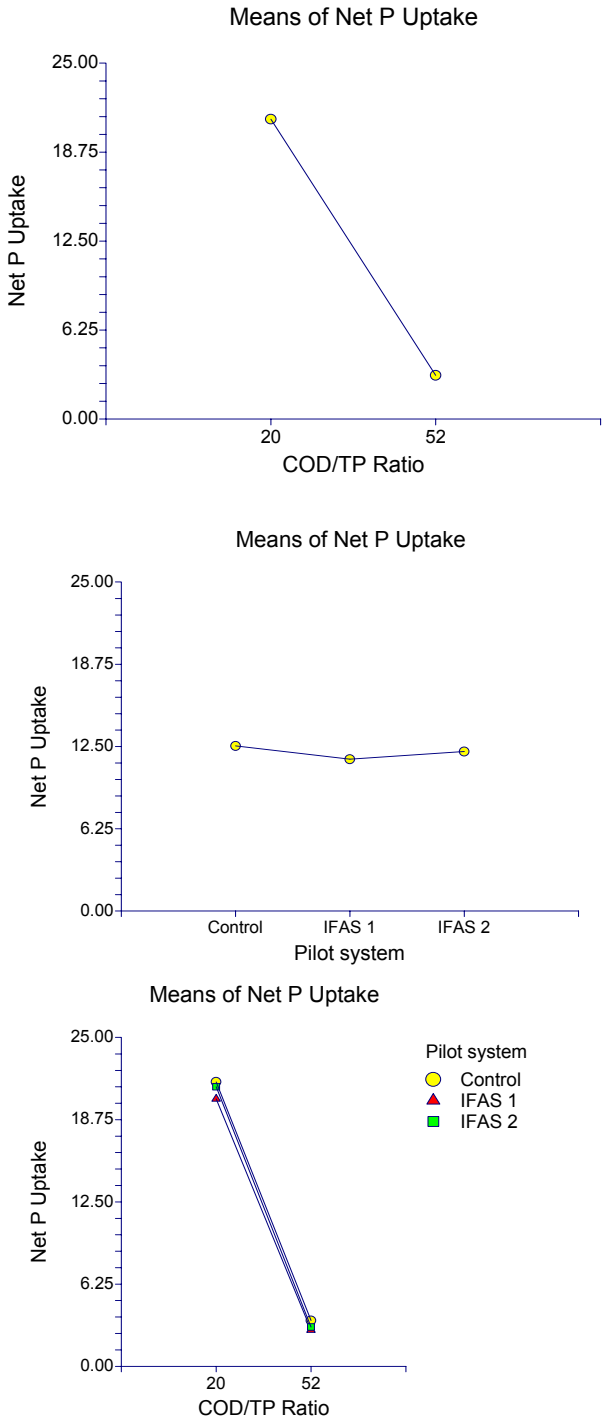


Figure 1. Means of net phosphorus uptake

Response: Total Denitrification
Hypothesis:

H_O = There is no effect of COD/TP ratio on the mean total denitrification
H_A = There is an effect of COD/TP ratio on the mean total denitrification

H_O = There is no difference in mean total denitrification between pilot systems
H_A = There is difference in mean total denitrification between pilot systems

H_O = There is no interaction of COD/TP ratio and pilot systems on the total denitrification
H_A = There is interaction of COD/TP ratio and pilot systems on the total denitrification

Expected Mean Squares Section:

Source Term	DF	Term Fixed?	Denominator Term	Expected Mean Square
A: COD/TP	1	Yes	S	S+bsA
B: Pilot System	2	Yes	S	S+asB
AB	2	Yes	S	S+sAB
S	18	No		S

Note: Expected Mean Squares are for the balanced cell-frequency case.

Analysis of Variance Table:

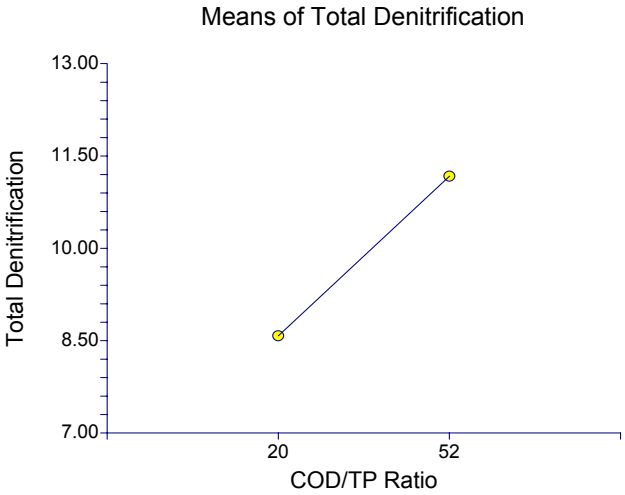
Source Term	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power (Alpha=0.05)
A: COD/TP Ratio	1	40.38	40.38	75.34	0.00*	1.00
B: Pilot system	2	2.99	1.50	2.79	0.09	0.48
AB	2	0.59	0.29	0.55	0.59	0.13
S	18	9.65	0.54			
Total (Adjusted)	23	53.61				
Total	24					

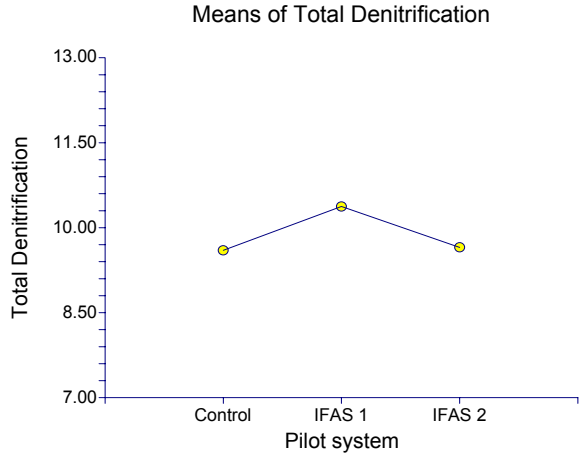
* Term significant at alpha = 0.05

Means and Effects Section:

Term	Count	Mean	Standard Error	Effect
All	24	9.88		9.88
A: COD/TP Ratio				
20	12	8.58	0.21	-1.30
52	12	11.17	0.21	1.30
B: Pilot system				
Control	8	9.60	0.26	-0.28
IFAS 1	8	10.38	0.26	0.50
IFAS 2	8	9.66	0.26	-0.22
AB: COD/TP Ratio,Pilot system				
20,Control	4	8.09	0.37	-0.22
20,IFAS 1	4	9.22	0.37	0.14
20,IFAS 2	4	8.43	0.37	7.46E-02
52,Control	4	11.12	0.37	0.22
52,IFAS 1	4	11.53	0.37	-0.14
52,IFAS 2	4	10.88	0.37	-7.46E-02

Plots Section:





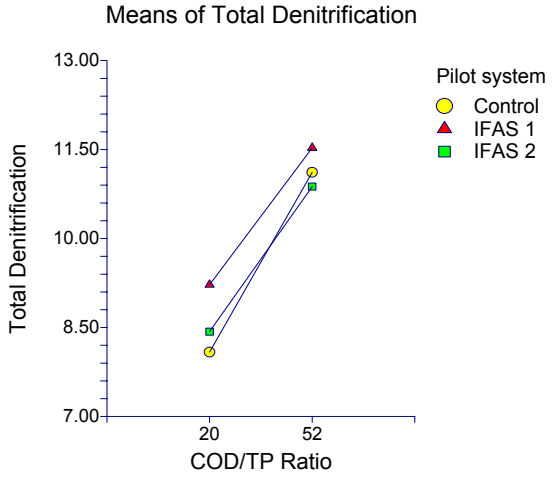


Figure 2. Means of total denitrification

Response:Total Nitrification
Hypothesis:

H_O = There is no effect of COD/TP ratio on the mean total nitrification
H_A = There is an effect of COD/TP ratio on the mean total nitrification

H_O = There is no difference in mean total nitrification between pilot systems
H_A = There is difference in mean total nitrification between pilot systems

H_O = There is no interaction of COD/TP ratio and pilot systems on the total nitrification
H_A = There is interaction of COD/TP ratio and pilot systems on the total nitrification

Expected Mean Squares Section:

Source Term	DF	Term Fixed?	Denominator Term	Expected Mean Square
A: COD/TP	1	Yes	S	S+bsA
B: Pilot System	2	Yes	S	S+asB
AB	2	Yes	S	S+sAB
S	18	No		S

Note: Expected Mean Squares are for the balanced cell-frequency case.

Analysis of Variance Table:

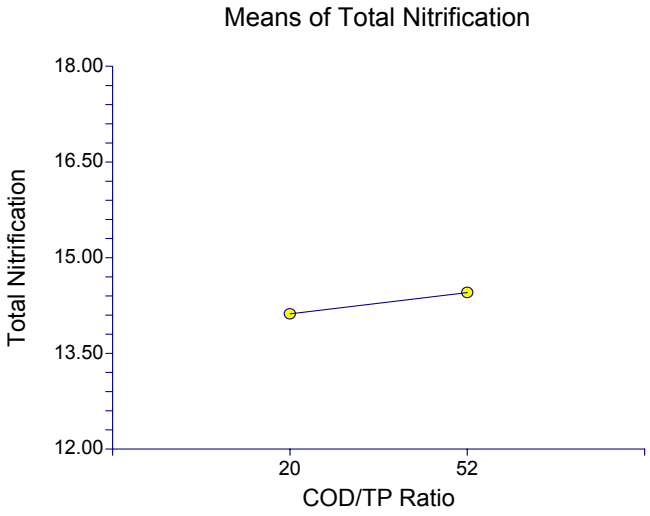
Source Term	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power (Alpha=0.05)
A: COD/TP Ratio	1	0.67	0.67	1.00	0.33	0.16
B: Pilot system	2	7.79	3.90	5.76	0.01*	0.80
AB	2	10.39	5.19	7.67	0.004*	0.91
S	18	12.18	0.68			
Total (Adjusted)	23	31.03				
Total	24					

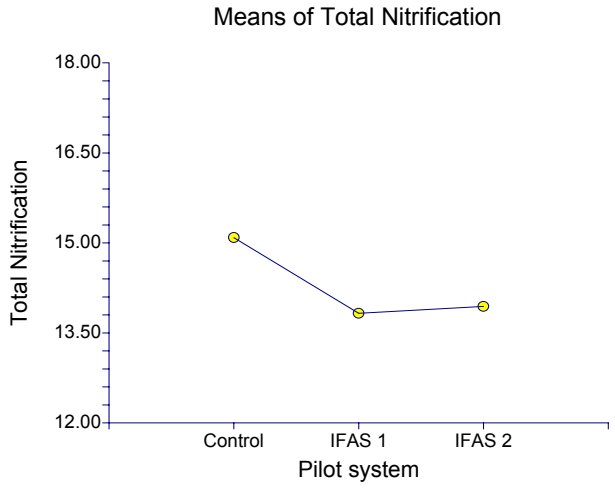
* Term significant at alpha = 0.05

Means and Effects Section:

Term	Count	Mean	Standard Error	Effect
All	24	14.29		14.29
A: COD/TP Ratio				
20	12	14.12	0.24	-0.17
52	12	14.45	0.24	0.17
B: Pilot system				
Control	8	15.09	0.29	0.80
IFAS 1	8	13.83	0.29	-0.46
IFAS 2	8	13.94	0.29	-0.34
AB: COD/TP Ratio,Pilot system				
20,Control	4	14.00	0.41	-0.92
20,IFAS 1	4	14.03	0.41	0.37
20,IFAS 2	4	14.33	0.41	0.56
52,Control	4	16.18	0.41	0.92
52,IFAS 1	4	13.63	0.41	-0.37
52,IFAS 2	4	13.55	0.41	-0.56

Plots Section:





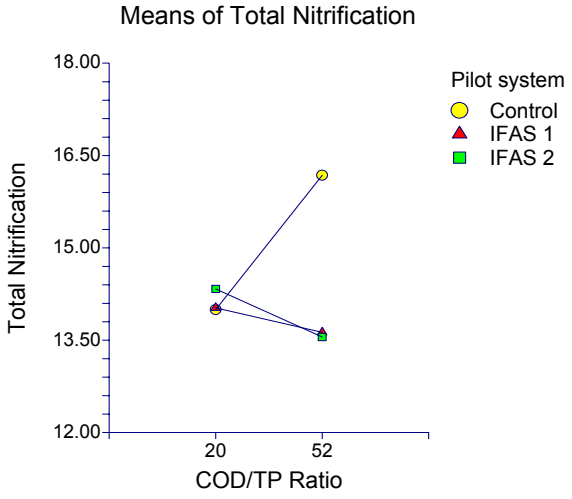


Figure 3. Means of total nitrification

APPENDIX B:

RAW DATA

Experimental Data Phase I

Table 1 Soluble COD concentrations and standard deviations during experiments phase I

Reactor	IFAS 1						
	03-Jun	10-Jun	13-Jun	17-Jun	Avg	SD	n
INF	652.80	580.80	564.00	620.40	604.50	39.95	4
ANA 1	107.52	108.42	135.36	101.52	113.21	15.08	4
ANA 2	92.16	100.67	97.76	71.44	90.51	13.19	4
ANX 1	53.76	38.72	45.12	26.32	40.98	11.55	4
ANX 2	53.76	30.98	45.12	26.32	39.05	12.65	4
AER 1	30.72	30.98	30.08	18.80	27.65	5.91	4
AER 2	30.72	30.98	30.08	18.80	27.65	5.91	4
AER 3	38.40	30.98	30.08	18.80	29.57	8.09	4
DEOX	30.20	30.98	30.08	18.80	27.52	5.82	4
EFF	38.40	30.98	30.08	18.80	29.57	8.09	4
Removed	614.40	549.82	533.92	601.60	574.94	39.08	4
% Removal	94.12	94.67	94.67	96.97	95.10	1.27	4
Reactor	**Control**						
	03-Jun	**10-Jun**	**13-Jun**	**17-Jun**	**Avg**	**SD**	**n**
INF	652.80	580.80	564.00	620.40	604.50	39.95	4
ANA 1	122.88	100.67	112.80	78.96	103.83	18.90	4
ANA 2	107.52	85.18	75.20	48.88	79.20	24.31	4
ANX 1	46.08	30.98	30.08	26.32	33.37	8.71	4
ANX 2	53.76	30.98	30.08	18.80	33.41	14.66	4
AER 1	38.76	30.98	30.08	18.80	29.66	8.22	4
AER 2	38.76	30.98	30.08	18.80	29.66	8.22	4
AER 3	46.06	30.98	30.08	18.80	31.48	11.19	4
DEOX	30.72	30.98	30.08	18.80	27.65	5.91	4
EFF	46.06	30.98	30.08	18.80	31.48	11.19	4
Removed	606.74	549.82	533.92	601.60	573.02	36.61	4
% Removal	92.94	94.67	94.67	96.97	94.81	1.65	4
Reactor	**IFAS 2**						
	03-Jun	**10-Jun**	**13-Jun**	**17-Jun**	**Avg**	**SD**	**n**
INF	652.80	580.80	564.00	620.40	604.50	39.95	4
ANA 1	145.92	170.37	180.48	139.12	158.97	19.64	4
ANA 2	130.56	0.00	157.92	124.08	103.14	70.31	4
ANX 1	38.76	30.98	37.60	26.32	33.42	5.84	4
ANX 2	38.76	23.23	37.60	18.80	29.60	10.09	4
AER 1	23.04	23.23	30.08	18.80	23.79	4.67	4
AER 2	30.72	23.23	30.08	18.80	25.71	5.72	4
AER 3	46.06	23.23	30.08	18.80	29.54	11.95	4
DEOX	30.72	23.23	30.08	18.80	25.71	5.72	4
EFF	46.06	23.23	30.08	18.80	29.54	11.95	4
Removed	606.74	557.57	533.92	601.60	574.96	35.15	4
% Removal	92.94	96.00	94.67	96.97	95.15	1.74	4

Table 2 Ammonium nitrogen concentrations and standard deviations during experiments phase I

Reactor		IFAS 1					
		10-Jun	13-Jun	17-Jun	Avg	SD	n
INF		64.40	72.80	78.40	71.87	7.05	3
ANA 1		31.81	33.18	34.74	33.24	1.47	3
ANA 2		31.22	32.11	34.49	32.61	1.69	3
ANX 1		18.88	21.52	22.40	20.93	1.83	3
ANX 2		19.39	19.76	21.74	20.30	1.26	3
AER 1		12.09	12.24	13.77	12.70	0.93	3
AER 2		3.04	3.07	3.68	3.26	0.36	3
AER 3		0.00	0.31	0.00	0.10	0.18	3
DEOX		0.00	0.00	0.00	0.00	0.00	3
EFF		0.00	0.00	0.00	0.00	0.00	3
Removed		64.40	72.80	78.40	71.87	7.05	3
% Removal		100.00	100.00	100.00	100.00	0.00	3
Reactor		**Control**					
		10-Jun	**13-Jun**	**17-Jun**	**Avg**	**SD**	**n**
INF		64.4	72.80	78.40	71.87	7.05	3
ANA 1		30.48	30.39	32.36	31.08	1.11	3
ANA 2		30.78	30.81	33.93	31.84	1.81	3
ANX 1		18.22	20.89	22.09	20.40	1.98	3
ANX 2		18.08	20.29	20.35	19.57	1.29	3
AER 1		7.73	10.05	10.65	9.48	1.54	3
AER 2		0.00	1.13	2.49	1.21	1.25	3
AER 3		0.00	0.00	0.00	0.00	0.00	3
DEOX		0.00	0.00	0.00	0.00	0.00	3
EFF		0.00	0.00	0.00	0.00	0.00	3
Removed		64.40	72.80	78.40	71.87	7.05	3
% Removal		100.00	100.00	100.00	100.00	0.00	3
Reactor		**IFAS 2**					
		10-Jun	**13-Jun**	**17-Jun**	**Avg**	**SD**	**n**
INF		64.40	72.80	78.40	71.87	7.05	3
ANA 1		35.84	34.05	35.00	34.96	0.90	3
ANA 2		35.87	37.22	38.07	37.05	1.11	3
ANX 1		19.46	20.51	21.09	20.35	0.83	3
ANX 2		18.49	20.77	21.14	20.13	1.44	3
AER 1		9.80	10.39	12.16	10.78	1.23	3
AER 2		0.00	1.48	1.58	1.02	0.88	3
AER 3		0.00	0.00	0.00	0.00	0.00	3
DEOX		0.00	0.00	0.00	0.00	0.00	3
EFF		0.00	0.00	0.00	0.00	0.00	3
Removed		64.40	72.80	78.40	71.87	7.05	3
% Removal		100.00	100.00	100.00	100.00	0.00	3

Table 3 Nitrate nitrogen concentrations and standard deviations during experiments phase I

Reactor	IFAS 1						
	03-Jun	10-Jun	13-Jun	17-Jun	Avg	SD	n
INF	0.00	0.00	0.00	2.10	0.53	1.05	4
ANA 1	0.00	0.00	0.00	0.00	0.00	0.00	4
ANA 2	0.00	0.00	0.00	0.00	0.00	0.00	4
ANX 1	0.00	0.68	0.00	2.40	0.77	1.13	4
ANX 2	0.00	0.00	0.00	1.30	0.33	0.65	4
AER 1	6.70	4.87	6.00	7.60	6.29	1.15	4
AER 2	10.80	12.31	11.40	15.90	12.60	2.28	4
AER 3	14.70	14.49	14.40	18.50	15.52	1.99	4
DEOX	11.90	13.49	13.80	18.10	14.32	2.65	4
EFF	14.60	13.99	14.50	18.40	15.37	2.04	4
Reactor	**Control**						
	03-Jun	**10-Jun**	**13-Jun**	**17-Jun**	**Avg**	**SD**	**n**
INF	0.00	0.00	0.00	2.10	0.53	1.05	4
ANA 1	0.00	0.00	0.00	1.20	0.30	0.60	4
ANA 2	0.00	0.00	0.00	0.90	0.23	0.45	4
ANX 1	0.90	0.00	0.43	3.40	1.18	1.52	4
ANX 2	0.90	0.00	0.00	2.20	0.78	1.04	4
AER 1	7.80	8.48	8.30	11.50	9.02	1.68	4
AER 2	15.40	14.82	14.40	17.50	15.53	1.38	4
AER 3	15.90	15.39	15.60	19.70	16.65	2.04	4
DEOX	12.50	14.54	14.40	19.20	15.16	2.85	4
EFF	15.50	15.03	15.00	18.80	16.08	1.83	4
Reactor	**IFAS 2**						
	03-Jun	**10-Jun**	**13-Jun**	**17-Jun**	**Avg**	**SD**	**n**
INF	0.00	0.00	0.00	2.10	0.53	1.05	4
ANA 1	0.00	0.18	0.00	1.20	0.35	0.58	4
ANA 2	0.00	0.00	0.00	0.00	0.00	0.00	4
ANX 1	0.90	0.63	0.79	3.20	1.38	1.22	4
ANX 2	0.90	0.61	0.00	1.90	0.85	0.79	4
AER 1	5.90	6.64	6.50	9.58	7.16	1.65	4
AER 2	14.30	14.66	14.40	17.40	15.19	1.48	4
AER 3	14.70	14.81	15.30	19.30	16.03	2.20	4
DEOX	14.60	13.68	14.70	18.90	15.47	2.33	4
EFF	14.90	13.52	15.00	19.00	15.61	2.36	4

*Nitrite concentrations were negligible.

Table 4 Phosphorus concentrations and standard deviations during experiments phase I

Reactor	IFAS 1						
	03-Jun	10-Jun	13-Jun	17-Jun	Avg	SD	n
INF	30.00	33.50	35.40	36.40	33.83	2.82	4
ANA 1	64.40	69.70	72.40	74.70	70.30	4.43	4
ANA 2	76.50	85.30	91.40	93.40	86.65	7.59	4
ANX 1	55.30	50.40	54.47	53.80	53.49	2.15	4
ANX 2	59.00	60.40	55.80	59.70	58.73	2.03	4
AER 1	37.80	40.80	35.80	39.30	38.43	2.14	4
AER 2	25.40	27.50	23.10	24.10	25.03	1.90	4
AER 3	11.40	14.70	11.30	15.30	13.18	2.12	4
DEOX	11.50	12.10	7.40	10.70	10.43	2.10	4
EFF	12.40	13.00	11.30	14.80	12.88	1.46	4
Removed	17.60	20.50	24.10	21.60	20.95	2.69	4
% Removal	62.00	56.12	68.08	57.97	61.04	5.30	4
Reactor	**Control**						
	03-Jun	10-Jun	13-Jun	17-Jun	Avg	SD	n
INF	30.00	33.50	35.40	36.40	33.83	2.82	4
ANA 1	63.40	80.10	75.80	80.40	74.93	7.97	4
ANA 2	79.00	98.20	99.50	104.80	95.38	11.28	4
ANX 1	51.90	49.40	52.40	53.30	51.75	1.67	4
ANX 2	57.20	50.80	56.10	51.30	53.85	3.27	4
AER 1	37.50	33.40	32.30	29.90	33.28	3.17	4
AER 2	18.50	17.20	20.40	19.80	18.98	1.42	4
AER 3	9.10	8.00	11.10	10.60	9.70	1.42	4
DEOX	8.50	4.50	8.30	6.70	7.00	1.85	4
EFF	10.40	7.80	10.80	10.90	9.98	1.47	4
Removed	19.60	25.70	24.60	25.50	23.85	2.87	4
% Removal	69.67	76.12	68.64	70.88	71.33	3.32	4
Reactor	**IFAS 2**						
	03-Jun	10-Jun	13-Jun	17-Jun	Avg	SD	n
INF	30.00	33.50	35.40	36.40	33.83	2.82	4
ANA 1	63.20	63.50	58.40	60.00	61.28	2.49	4
ANA 2	77.70	80.40	76.40	77.50	78.00	1.70	4
ANX 1	54.80	50.00	51.00	50.50	51.58	2.19	4
ANX 2	54.40	49.00	53.60	48.80	51.45	2.96	4
AER 1	31.40	33.50	53.30	48.20	41.60	10.80	4
AER 2	16.70	17.70	19.50	20.80	18.68	1.83	4
AER 3	7.90	8.90	11.70	12.00	10.13	2.04	4
DEOX	7.30	5.70	7.60	7.60	7.05	0.91	4
EFF	10.70	5.80	11.30	12.80	10.15	3.03	4
Removed	19.30	27.70	24.10	23.60	23.68	3.44	4
% Removal	73.67	73.43	66.95	67.03	70.27	3.79	4

Table 5 Solid concentrations and standard deviations during experiments phase I

MLVSS							
Reactor	**IFAS 1**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	2250.00	2420.00	2430.00	2090.00	2297.50	161.12	4
ANX 2	3060.00	3320.00	3500.00	3050.00	3232.50	217.77	4
AER 3	2930.00	3150.00	3450.00	3000.00	3132.50	230.71	4
EFF	12.00	17.00	21.00	22.00	18.00	4.55	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	2370.00	2810.00	2510.00	2320.00	2502.50	220.21	4
ANX 2	3270.00	4440.00	3410.00	3400.00	3630.00	543.75	4
AER 3	3140.00	3590.00	3340.00	3210.00	3320.00	198.16	4
EFF	16.00	30.00	12.00	19.00	19.25	7.72	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	1980.00	1990.00	1910.00	2050.00	1982.50	57.37	4
ANX 2	3540.00	3460.00	3470.00	3250.00	3430.00	125.17	4
AER 3	3380.00	4430.00	3930.00	3120.00	3715.00	584.15	4
EFF	34.00	13.00	24.00	10.00	20.25	10.97	4
MLSS							
Reactor	**IFAS 1**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	2900.00	3270.00	3150.00	2670.00	2997.50	267.25	4
ANX 2	3970.00	4480.00	4720.00	4180.00	4337.50	329.89	4
AER 3	3950.00	4470.00	4820.00	4200.00	4360.00	373.01	4
EFF	12.00	23.00	19.00	23.00	19.25	5.19	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	3010.00	3740.00	3300.00	3050.00	3275.00	335.51	4
ANX 2	4320.00	6070.00	4780.00	4820.00	4997.50	750.13	4
AER 3	4380.00	5220.00	4830.00	4770.00	4800.00	343.80	4
EFF	16.00	41.00	9.00	23.00	22.25	13.74	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	2570.00	2700.00	2540.00	2630.00	2610.00	70.71	4
ANX 2	4790.00	4870.00	4840.00	4640.00	4785.00	102.14	4
AER 3	4770.00	6380.00	5680.00	5000.00	5457.50	726.29	4
EFF	49.00	20.00	28.00	13.00	27.50	15.59	4

Experimental Data Phase II

Table 6 Soluble COD concentrations and standard deviations during experiments phase II

Reactor	IFAS 1						
	30-Jan	03-Feb	06-Feb	10-Feb	Avg	SD	n
INF	709.82	652.14	594.06	744.30	675.08	66.05	4
ANA 1	108.24	116.16	103.25	136.64	116.07	14.71	4
ANA 2	68.88	109.71	77.44	117.12	93.29	23.70	4
ANX 1	29.52	45.17	32.27	78.08	46.26	22.28	4
ANX 2	29.52	38.72	25.81	39.04	33.27	6.65	4
AER 1	29.52	38.72	25.81	39.04	33.27	6.65	4
AER 2	29.52	38.72	25.81	39.04	33.27	6.65	4
AER 3	29.52	38.72	25.81	39.04	33.27	6.65	4
DEOX	29.52	38.72	32.27	39.04	34.89	4.75	4
EFF	29.52	38.72	25.81	39.04	33.27	6.65	4
Removed	680.30	613.42	568.25	705.26	641.81	62.52	4
% Removal	95.84	94.06	95.66	94.75	95.08	0.83	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	709.82	652.14	594.06	744.30	675.08	66.05	4
ANA 1	68.88	96.68	103.25	97.60	91.60	15.42	4
ANA 2	68.88	83.89	77.44	87.84	79.51	8.28	4
ANX 1	29.52	51.63	25.81	39.04	36.50	11.52	4
ANX 2	29.52	38.72	25.81	39.04	33.27	6.65	4
AER 1	29.52	38.72	25.81	39.04	33.27	6.65	4
AER 2	29.52	38.72	25.81	39.04	33.27	6.65	4
AER 3	29.52	38.72	25.81	39.04	33.27	6.65	4
DEOX	29.52	38.72	25.81	39.04	33.27	6.65	4
EFF	29.52	38.72	25.81	39.04	33.27	6.65	4
Removed	680.30	613.42	568.25	705.26	641.81	62.52	4
% Removal	95.84	94.06	95.66	94.75	95.08	0.83	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	709.82	652.14	594.06	744.30	675.08	66.05	4
ANA 1	108.24	90.35	83.89	87.84	92.58	10.77	4
ANA 2	68.88	83.89	77.44	58.56	72.19	10.97	4
ANX 1	29.52	38.72	32.27	39.04	34.89	4.75	4
ANX 2	29.52	38.72	32.27	39.04	34.89	4.75	4
AER 1	29.52	38.72	32.27	39.04	34.89	4.75	4
AER 2	29.52	38.72	32.27	39.04	34.89	4.75	4
AER 3	29.52	38.72	32.27	39.04	34.89	4.75	4
DEOX	29.52	38.72	32.27	39.04	34.89	4.75	4
EFF	29.52	38.72	32.27	39.04	34.89	4.75	4
Removed	680.30	613.42	561.79	705.26	640.19	65.08	4
% Removal	95.84	94.06	94.57	94.75	94.81	0.75	4

Table 7 Ammonium nitrogen concentrations and standard deviations during experiments phase II

Reactor	IFAS 1						
	30-Jan	03-Feb	06-Feb	10-Feb	Avg	SD	n
INF	109.20	92.40	103.60	106.40	102.90	7.36	4
ANA 1	51.87	46.41	46.36	47.34	48.00	2.62	4
ANA 2	51.17	45.30	49.83	48.33	48.66	2.52	4
ANX 1	26.82	26.52	27.73	21.84	25.73	2.64	4
ANX 2	25.97	23.76	26.32	21.25	24.33	2.34	4
AER 1	20.61	16.67	19.00	16.67	18.24	1.93	4
AER 2	13.98	8.28	12.89	12.08	11.81	2.48	4
AER 3	5.39	3.21	7.55	6.40	5.64	1.84	4
DEOX	4.68	1.34	5.93	5.83	4.45	2.15	4
EFF	3.91	1.95	7.81	5.07	4.69	2.45	4
Removed	105.29	90.45	95.79	101.33	98.22	6.48	4
% Removal	96.42	97.89	92.46	95.23	95.50	2.30	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	109.20	92.40	103.60	106.40	102.90	7.36	4
ANA 1	45.80	44.87	46.19	46.55	45.85	0.72	4
ANA 2	46.90	47.07	47.35	48.92	47.56	0.93	4
ANX 1	23.02	24.42	25.34	20.36	23.29	2.17	4
ANX 2	23.20	23.02	24.87	20.49	22.90	1.81	4
AER 1	16.03	16.97	15.30	12.63	15.23	1.86	4
AER 2	6.89	8.07	6.53	5.63	6.78	1.01	4
AER 3	2.27	0.95	2.39	2.16	1.94	0.67	4
DEOX	0.42	0.00	1.83	1.37	0.91	0.84	4
EFF	0.53	0.72	0.00	0.93	0.55	0.40	4
Removed	108.67	91.68	103.60	105.47	102.36	7.42	4
% Removal	99.51	99.22	100.00	99.13	99.47	0.39	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	109.20	92.40	103.60	106.40	102.90	7.36	4
ANA 1	52.81	42.87	47.23	45.04	46.99	4.27	4
ANA 2	51.54	44.93	45.92	44.75	46.79	3.21	4
ANX 1	34.78	23.90	24.56	20.11	25.84	6.28	4
ANX 2	31.80	22.68	22.36	19.65	24.12	5.30	4
AER 1	21.58	15.61	18.32	11.84	16.84	4.13	4
AER 2	10.51	6.89	10.29	4.36	8.01	2.95	4
AER 3	1.69	2.55	3.30	2.18	2.43	0.68	4
DEOX	1.21	1.41	1.31	0.64	1.14	0.34	4
EFF	1.48	2.03	1.84	0.00	1.34	0.92	4
Removed	107.72	90.37	101.76	106.40	101.56	7.89	4
% Removal	98.64	97.80	98.22	100.00	98.67	0.95	4

Table 8 Nitrate nitrogen concentrations and standard deviations during experiments phase II

NO3-N							
Reactor	**IFAS 1**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	0.00	0.00	0.37	0.42	0.20	0.23	4
ANA 1	0.95	0.05	2.43	0.09	0.88	1.11	4
ANA 2	0.62	0.61	0.10	0.09	0.35	0.30	4
ANX 1	9.50	9.33	9.62	13.01	10.37	1.77	4
ANX 2	9.33	9.18	6.71	11.93	9.29	2.13	4
AER 1	15.26	15.45	14.45	16.29	15.36	0.76	4
AER 2	21.43	22.69	20.71	20.73	21.39	0.93	4
AER 3	28.14	27.33	26.35	25.11	26.73	1.31	4
DEOX	27.73	27.80	26.37	23.21	26.28	2.15	4
EFF	27.27	27.66	24.57	23.69	25.80	1.96	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	0.00	0.00	0.37	0.42	0.20	0.23	4
ANA 1	0.71	0.04	0.24	0.81	0.45	0.37	4
ANA 2	0.14	0.67	0.51	0.29	0.40	0.23	4
ANX 1	14.97	10.92	14.84	19.75	15.12	3.61	4
ANX 2	13.18	9.42	11.70	17.82	13.03	3.55	4
AER 1	19.69	14.83	21.26	24.55	20.08	4.05	4
AER 2	27.79	23.20	29.03	30.78	27.70	3.24	4
AER 3	32.64	28.30	33.21	33.76	31.98	2.49	4
DEOX	32.67	28.40	33.07	33.22	31.84	2.31	4
EFF	32.82	27.97	33.20	33.11	31.78	2.54	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	0.00	0.00	0.37	0.42	0.20	0.23	4
ANA 1	0.02	0.82	0.70	0.66	0.55	0.36	4
ANA 2	0.81	0.62	0.03	0.63	0.52	0.34	4
ANX 1	8.18	12.31	12.93	19.33	13.19	4.61	4
ANX 2	7.31	11.52	12.45	18.75	12.51	4.72	4
AER 1	17.96	19.36	18.35	24.84	20.13	3.20	4
AER 2	29.03	26.71	26.45	30.65	28.21	2.00	4
AER 3	35.86	29.88	32.78	33.57	33.02	2.47	4
DEOX	35.78	30.87	33.01	33.92	33.40	2.04	4
EFF	35.01	30.82	31.76	33.40	32.75	1.85	4

*Nitrite concentrations were negligible.

Table 9 Phosphorus concentrations and standard deviations during experiments phase II

Reactor	IFAS 1						
	30-Jan	03-Feb	06-Feb	10-Feb	Avg	SD	n
INF	34.01	34.17	33.53	32.43	33.54	0.79	4
ANA 1	45.86	42.73	44.41	38.43	42.86	3.22	4
ANA 2	61.77	56.21	60.63	47.97	56.64	6.26	4
ANX 1	32.00	36.35	34.63	26.91	32.47	4.12	4
ANX 2	31.96	33.54	35.35	26.92	31.94	3.62	4
AER 1	21.08	24.58	29.99	21.76	24.35	4.05	4
AER 2	14.53	18.37	16.88	17.98	16.94	1.73	4
AER 3	10.27	14.46	12.31	15.28	13.08	2.25	4
DEOX	9.62	12.40	12.33	15.42	12.44	2.37	4
EFF	9.82	11.90	14.19	16.94	13.21	3.06	4
Removed	24.19	22.27	19.34	15.49	20.32	3.79	4
% Removal	69.81	57.68	63.29	52.88	60.92	7.30	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	34.01	34.17	33.53	32.43	33.54	0.79	4
ANA 1	53.04	47.88	48.73	44.90	48.64	3.36	4
ANA 2	75.00	64.33	64.87	62.67	66.72	5.60	4
ANX 1	35.13	34.43	35.27	28.13	33.24	3.43	4
ANX 2	35.66	33.59	35.67	28.52	33.36	3.37	4
AER 1	25.02	24.43	25.56	22.41	24.36	1.38	4
AER 2	18.34	17.56	19.97	18.11	18.50	1.04	4
AER 3	11.25	11.38	13.70	14.27	12.65	1.56	4
DEOX	9.79	10.15	13.10	12.22	11.31	1.60	4
EFF	10.83	10.78	13.11	12.97	11.92	1.29	4
Removed	23.18	23.39	20.42	19.46	21.61	1.97	4
% Removal	66.93	66.70	59.14	56.00	62.19	5.49	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
INF	34.01	34.17	33.53	32.43	33.54	0.79	4
ANA 1	58.43	43.98	48.42	42.26	48.27	7.25	4
ANA 2	70.24	59.15	60.88	59.99	62.56	5.16	4
ANX 1	52.02	34.53	37.58	26.68	37.70	10.59	4
ANX 2	50.50	32.86	39.77	25.56	37.17	10.61	4
AER 1	32.40	24.29	29.40	19.78	26.47	5.58	4
AER 2	20.71	17.86	22.97	15.44	19.24	3.29	4
AER 3	11.62	11.94	15.81	11.45	12.70	2.08	4
DEOX	8.29	10.06	14.23	10.02	10.65	2.52	4
EFF	9.77	11.44	16.78	11.15	12.28	3.08	4
Removed	24.24	22.73	16.75	21.28	21.25	3.24	4
% Removal	65.85	65.06	52.85	64.69	62.11	6.19	4

Table 10 Solid concentrations and standard deviations during experiments phase II

MLVSS							
Reactor	**IFAS 1**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	1730.00	1410.00	1660.00	1430.00	1557.50	161.53	4
ANX 2	3390.00	3430.00	3130.00	2280.00	3057.50	535.12	4
AER 3	3010.00	2230.00	2690.00	1980.00	2477.50	460.97	4
EFF	22.00	43.00	43.00	48.00	39.00	11.58	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	2150.00	1690.00	1610.00	1780.00	1807.50	238.66	4
ANX 2	3100.00	3530.00	3080.00	3100.00	3202.50	218.54	4
AER 3	2880.00	2740.00	2770.00	2660.00	2762.50	91.06	4
EFF	25.00	32.00	38.00	34.00	32.25	5.44	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	1530.00	1320.00	1220.00	1530.00	1400.00	155.56	4
ANX 2	2640.00	2080.00	2160.00	2490.00	2342.50	266.13	4
AER 3	2580.00	2130.00	1950.00	2750.00	2352.50	374.73	4
EFF	30.00	51.00	22.00	26.00	32.25	12.92	4
MLSS							
Reactor	**IFAS 1**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	2160.00	1630.00	2090.00	1740.00	1905.00	259.55	4
ANX 2	4360.00	4550.00	4000.00	2980.00	3972.50	699.87	4
AER 3	4120.00	3020.00	3620.00	2600.00	3340.00	667.53	4
EFF	34.00	60.00	60.00	54.00	52.00	12.33	4
Reactor	**Control**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	2660.00	2100.00	2090.00	2110.00	2240.00	280.12	4
ANX 2	4230.00	4800.00	4150.00	4280.00	4365.00	294.90	4
AER 3	4690.00	3890.00	3870.00	3650.00	4025.00	456.47	4
EFF	38.00	44.00	56.00	44.00	45.50	7.55	4
Reactor	**IFAS 2**						
	30-Jan	**03-Feb**	**06-Feb**	**10-Feb**	**Avg**	**SD**	**n**
ANA 2	1920.00	1690.00	1520.00	1910.00	1760.00	192.01	4
ANX 2	3680.00	2830.00	2920.00	3320.00	3187.50	391.35	4
AER 3	3790.00	2920.00	2760.00	3650.00	3280.00	515.43	4
EFF	46.00	72.00	64.00	40.00	55.50	15.00	4

Experimental Data Phase III

Table 11 Soluble COD concentrations and standard deviations during experiments phase III

Reactor	IFAS 1						
	29-May	1-Jun	8-Jun	9-Jun	Avg	SD	n
INF	579.13	560.00	587.35	610.68	584.29	21.00	4
ANA 1	170.80	152.32	183.92	171.36	169.01	13.02	4
ANA 2	161.04	152.32	183.92	152.32	165.76	14.92	4
ANX 1	24.40	19.04	48.40	38.08	30.61	13.30	4
ANX 2	24.40	19.04	29.04	38.08	24.16	8.07	4
AER 1	24.40	38.08	29.04	19.04	30.51	8.07	4
AER 2	24.40	19.04	29.04	19.04	24.16	4.82	4
AER 3	24.40	28.56	29.04	19.04	27.33	4.64	4
DEOX	24.40	38.08	38.72	38.08	33.73	6.95	4
EFF	24.40	38.08	29.04	19.04	30.51	8.07	4
Removed	554.73	521.92	558.31	591.64	544.99	28.50	4
% Removal	95.79	93.20	95.06	96.88	94.68	1.55	4
Reactor	**Control**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	579.13	560.00	587.35	610.68	584.29	21.00	4
ANA 1	141.52	114.24	154.68	133.28	136.81	16.93	4
ANA 2	102.48	114.24	154.68	152.32	123.80	26.52	4
ANX 1	24.40	19.04	29.04	19.04	24.16	4.82	4
ANX 2	24.40	28.56	34.85	38.08	29.27	6.15	4
AER 1	24.40	19.04	38.72	19.04	27.39	9.30	4
AER 2	24.40	47.60	19.94	19.04	30.65	13.44	4
AER 3	24.40	9.52	38.84	19.04	24.25	12.25	4
DEOX	24.40	19.04	19.36	38.08	20.93	8.92	4
EFF	24.40	19.04	34.21	19.04	25.88	7.15	4
Removed	554.73	540.96	553.14	591.64	549.61	21.90	4
% Removal	95.79	96.60	94.18	96.88	95.52	1.22	4
Reactor	**IFAS 2**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	579.13	560.00	587.35	610.68	584.29	21.00	4
ANA 1	170.80	161.84	193.60	171.36	175.41	13.52	4
ANA 2	151.28	152.32	193.60	152.32	165.73	20.82	4
ANX 1	24.04	38.08	38.72	19.04	33.61	9.95	4
ANX 2	24.04	19.04	19.36	19.04	20.81	2.45	4
AER 1	24.04	19.04	19.36	19.04	20.81	2.45	4
AER 2	24.04	28.56	29.04	19.04	27.21	4.67	4
AER 3	24.04	28.56	19.36	19.04	23.99	4.50	4
DEOX	24.04	38.08	19.36	19.04	27.16	8.93	4
EFF	24.04	57.12	38.72	19.04	39.96	17.10	4
Removed	555.09	502.88	548.63	591.64	535.53	36.43	4
% Removal	95.85	89.80	93.41	96.88	93.02	3.15	4

Table 12 Ammonium concentrations and standard deviations during experiments phase III

Reactor	IFAS 1						
	29-May	1-Jun	8-Jun	9-Jun	Avg	SD	n
INF	107.80	114.80	114.80	106.40	110.95	4.48	4
ANA 1	58.24	67.93	66.85	63.28	64.34	4.37	4
ANA 2	60.26	63.97	69.46	59.95	64.56	4.43	4
ANX 1	30.92	36.70	36.97	35.56	34.86	2.81	4
ANX 2	31.65	36.92	35.11	33.57	34.56	2.24	4
AER 1	23.83	28.33	28.85	27.83	27.00	2.29	4
AER 2	20.08	27.67	24.89	22.59	24.21	3.24	4
AER 3	14.46	24.35	20.46	17.51	19.76	4.22	4
DEOX	13.42	23.18	19.05	16.42	18.55	4.14	4
EFF	15.97	23.80	15.81	14.98	18.53	4.13	4
Removed	91.83	91.00	98.99	91.42	93.94	3.80	4
% Removal	85.19	79.27	86.23	85.92	83.56	3.28	4
Reactor	**Control**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	107.80	114.80	114.80	106.40	110.95	4.48	4
ANA 1	47.77	49.27	59.91	47.19	52.32	5.98	4
ANA 2	44.41	57.04	65.50	55.35	55.65	8.67	4
ANX 1	18.94	24.07	28.29	26.42	23.77	4.05	4
ANX 2	17.06	21.38	26.49	24.04	21.64	4.04	4
AER 1	8.79	15.66	18.47	14.98	14.31	4.08	4
AER 2	0.78	0.00	8.55	0.00	3.11	4.16	4
AER 3	0.00	0.00	0.00	0.00	0.00	0.00	4
DEOX	0.00	0.00	0.00	0.00	0.00	0.00	4
EFF	0.00	0.00	0.00	0.00	0.00	0.00	4
Removed	107.80	114.80	114.80	106.40	112.47	4.48	4
% Removal	100.00	100.00	100.00	100.00	100.00	0.00	4
Reactor	**IFAS 2**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	107.80	114.80	114.80	106.40	110.95	4.48	4
ANA 1	59.76	67.20	65.51	59.27	64.16	4.01	4
ANA 2	60.60	62.72	71.44	59.78	64.92	5.35	4
ANX 1	34.63	40.57	42.31	35.86	39.17	3.68	4
ANX 2	32.70	38.38	39.37	30.77	36.82	4.22	4
AER 1	28.68	34.59	33.79	26.71	32.35	3.85	4
AER 2	21.84	27.55	27.81	19.99	25.73	3.98	4
AER 3	16.77	24.92	23.51	13.20	21.73	5.55	4
DEOX	15.87	13.78	21.71	10.08	17.12	4.86	4
EFF	16.97	20.45	21.86	11.90	19.76	4.43	4
Removed	90.83	94.35	92.94	94.50	92.71	1.70	4
% Removal	84.26	82.19	80.96	88.82	82.47	3.45	4

Table 13 Nitrate concentrations and standard deviations during experiments phase III

Reactor	IFAS 1						
	29-May	1-Jun	8-Jun	9-Jun	Avg	SD	n
INF	1.20	0.00	0.56	0.63	0.20	0.23	4
ANA 1	0.00	0.00	0.64	0.58	0.88	1.11	4
ANA 2	1.17	0.00	0.00	0.62	0.35	0.30	4
ANX 1	3.52	2.30	3.86	2.60	10.37	1.77	4
ANX 2	2.29	1.69	1.79	1.74	9.29	2.13	4
AER 1	5.15	3.26	5.64	4.93	15.36	0.76	4
AER 2	8.77	6.63	10.67	9.68	21.39	0.93	4
AER 3	12.40	10.39	15.04	14.76	26.73	1.31	4
DEOX	12.44	10.12	15.46	14.66	26.28	2.15	4
EFF	13.18	10.50	15.46	14.61	25.80	1.96	4
Reactor	**Control**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	1.20	0.00	0.56	0.63	0.20	0.23	4
ANA 1	1.13	0.00	0.00	0.00	0.45	0.37	4
ANA 2	0.00	0.00	0.54	0.00	0.40	0.23	4
ANX 1	12.05	9.84	10.62	10.08	15.12	3.61	4
ANX 2	11.18	6.56	7.78	7.26	13.03	3.55	4
AER 1	17.93	15.05	16.43	15.63	20.08	4.05	4
AER 2	23.13	20.29	23.16	18.99	27.70	3.24	4
AER 3	23.04	26.14	28.47	26.91	31.98	2.49	4
DEOX	23.65	26.87	25.18	27.28	31.84	2.31	4
EFF	23.45	26.80	29.00	27.04	31.78	2.54	4
Reactor	**IFAS 2**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	1.20	0.00	0.56	0.63	0.20	0.23	4
ANA 1	1.16	0.00	0.56	0.60	0.55	0.36	4
ANA 2	1.21	0.00	0.55	0.56	0.52	0.34	4
ANX 1	3.24	2.84	2.04	3.31	13.19	4.61	4
ANX 2	3.34	1.59	0.75	1.63	12.51	4.72	4
AER 1	5.57	3.00	4.28	6.35	20.13	3.20	4
AER 2	6.56	5.44	7.37	9.97	28.21	2.00	4
AER 3	13.27	9.62	11.60	16.09	33.02	2.47	4
DEOX	13.64	9.58	11.90	16.22	33.40	2.04	4
EFF	13.59	9.62	12.08	15.85	32.75	1.85	4

*Nitrite concentrations were negligible.

Table 14 Phosphorus concentrations and standard deviations during experiments phase III

Reactor	IFAS 1						
	29-May	1-Jun	8-Jun	9-Jun	Avg	SD	n
INF	10.89	10.51	12.49	10.95	11.21	0.88	4
ANA 1	10.16	9.47	11.51	10.68	10.38	0.86	4
ANA 2	11.18	10.25	11.77	11.08	11.07	0.63	4
ANX 1	9.49	9.10	10.33	9.48	9.64	0.52	4
ANX 2	9.35	9.25	10.37	9.46	9.66	0.52	4
AER 1	8.23	6.61	9.39	7.89	8.08	1.14	4
AER 2	8.70	8.44	9.31	8.75	8.82	0.37	4
AER 3	8.15	8.25	9.27	8.47	8.56	0.51	4
DEOX	8.09	8.23	8.99	8.28	8.44	0.40	4
EFF	8.36	8.13	9.07	8.35	8.52	0.41	4
Removed	2.53	2.38	3.42	2.60	2.78	0.47	4
% Removal	25.16	21.50	25.78	22.65	24.15	2.03	4
Reactor	**Control**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	10.89	10.51	12.49	10.95	11.21	0.88	4
ANA 1	10.48	9.51	11.62	10.86	10.54	0.88	4
ANA 2	10.72	11.47	13.10	12.06	11.76	1.00	4
ANX 1	9.53	9.94	10.56	10.26	10.01	0.44	4
ANX 2	9.30	9.28	10.14	9.60	9.57	0.40	4
AER 1	8.58	8.77	9.77	8.96	9.04	0.52	4
AER 2	7.89	7.05	8.94	7.69	7.96	0.78	4
AER 3	7.43	7.61	8.48	7.68	7.84	0.47	4
DEOX	6.62	7.41	8.05	7.59	7.36	0.60	4
EFF	6.52	7.39	8.51	7.79	7.47	0.83	4
Removed	4.37	3.12	3.98	3.16	3.82	0.62	4
% Removal	31.77	27.59	32.11	29.86	30.49	2.08	4
Reactor	**IFAS 2**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
INF	10.89	10.51	12.49	10.95	11.21	0.88	4
ANA 1	9.59	9.73	10.53	10.49	9.95	0.49	4
ANA 2	11.82	10.69	13.42	12.35	11.98	1.14	4
ANX 1	9.92	9.37	11.03	8.97	10.11	0.89	4
ANX 2	9.71	9.39	11.20	9.85	10.10	0.80	4
AER 1	9.37	9.03	10.20	8.96	9.53	0.57	4
AER 2	8.39	6.94	9.23	7.51	8.19	1.00	4
AER 3	8.29	7.75	7.77	7.81	7.94	0.26	4
DEOX	8.20	7.67	8.73	5.71	8.20	1.32	4
EFF	8.12	7.75	9.21	7.83	8.36	0.67	4
Removed	2.77	2.76	3.28	3.12	2.94	0.26	4
% Removal	23.88	26.26	37.79	28.68	29.31	6.08	4

Table 15 Phosphorus concentrations and standard deviations during experiments phase III

MLVSS							
Reactor	**IFAS 1**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
ANA 2	920.00	773.50	1170.00	900.00	940.88	165.95	4
ANX 2	1500.00	1730.00	1890.00	2150.00	1817.50	273.42	4
AER 3	1670.00	1640.00	1730.00	1620.00	1665.00	47.96	4
EFF	24.00	25.00	22.00	16.00	21.75	4.03	4
Reactor	**Control**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
ANA 2	1350.00	1230.00	1180.00	1130.00	1222.50	94.30	4
ANX 2	2500.00	2190.00	2280.00	2250.00	2305.00	135.28	4
AER 3	2370.00	2210.00	2300.00	2320.00	2300.00	66.83	4
EFF	14.00	20.00	20.00	26.00	20.00	4.90	4
Reactor	**IFAS 2**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
ANA 2	1050.00	1050.00	1140.00	1200.00	1110.00	73.48	4
ANX 2	1770.00	1800.00	2030.00	1960.00	1890.00	125.17	4
AER 3	1640.00	1620.00	1940.00	2120.00	1830.00	242.49	4
EFF	22.00	28.00	30.00	14.00	23.50	7.19	4
MLSS							
Reactor	**IFAS 1**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
ANA 2	1090.00	910.00	1320.00	1050.00	1092.50	170.17	4
ANX 2	1740.00	1980.00	2190.00	2490.00	2100.00	318.43	4
AER 3	1920.00	1720.00	2000.00	1930.00	1892.50	120.38	4
EFF	30.00	28.00	27.00	16.00	25.25	6.29	4
Reactor	**Control**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
ANA 2	1610.00	1330.00	1400.00	1320.00	1415.00	134.78	4
ANX 2	2940.00	2470.00	2620.00	2600.00	2657.50	199.73	4
AER 3	2810.00	2470.00	2730.00	2680.00	2672.50	145.23	4
EFF	19.00	24.00	24.00	33.00	25.00	5.83	4
Reactor	**IFAS 2**						
	29-May	**1-Jun**	**8-Jun**	**9-Jun**	**Avg**	**SD**	**n**
ANA 2	1270.00	1200.00	1409.00	1340.00	1304.75	89.98	4
ANX 2	2060.00	1910.00	2390.00	2330.00	2172.50	226.33	4
AER 3	1900.00	1750.00	2300.00	2420.00	2092.50	318.68	4
EFF	24.00	33.00	37.00	28.00	30.50	5.69	4

VITA

Tongchai Sriwiriyarat was born August 19, 1971 in Thailand. He graduated with a Bachelor of Science in Sanitary Science, presently named Environmental Health Science, from the school of Public Health, Mahidol University, Bangkok, Thailand.

After graduation with first class honors, Tongchai was awarded a scholarship from the Royal Thai Government to pursue M.S. and Ph.D. degrees in Environmental Engineering in the United States of America. As one of the Royal Thai Scholarship requirements, he joined the Faculty of Engineering at Burapha University as a faculty member. After one year, he left the country to pursue his degrees at Virginia Polytechnic Institute and State University. Under advisement of Dr. Clifford W. Randall, his research area was focused on a computer program development for the IFAS (Integrated Fixed Film Activated Sludge) wastewater treatment processes and IFAS related researches. Upon his Master degree completion, he continued to pursue his Ph.D. with the same department. After he finished his Ph.D., he returned back to Thailand and is now working in the Civil Engineering department and trying to initiate an Environmental Engineering program at Burapha University.

Education

- B.S. Environmental Health Science, Mahidol University, 1994
- M.S. Environmental Engineering, Virginia Polytechnic Institute and State University, 1999
- Ph.D. Civil Engineering, Virginia Polytechnic Institute and State University, 2002

Permanent Address

- Faculty of Engineering, Department of Civil Engineering, Tumbon Saensook, Amphur Muang, Chonburi, 20131. Thailand.
- E-mail: sriwiri@buu.ac.th