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Review

Activated Sludge and Other Aerobic Suspended Culture Processes

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Abstract: A review of the literature published in 2008, 2009 and 2010 relating to activated sludge treatment of wastewater is presented. The review considers information on the topics of modeling and kinetics; process microbiology; nitrogen and phosphorus removal; treatment and effects of xenobiotics; oxygen transfer; and solids separation.

Keywords: activated sludge; wastewater treatment; pollution prevention

1. Introduction

The scope of research being conducted in the field of activated sludge wastewater treatment has grown steadily as scientific understanding of fundamental microbial behavior has increased and more sophisticated engineering designs have been developed to modify the basic process. The objective of this paper is to review some of the major research results on the topic of activated sludge treatment published in 2008, 2009 and 2010. Since there is so much information available for this period, this review presents a sample of the available findings in the selected areas of modeling and kinetics, process microbiology, nitrogen and phosphorus removal, treatment and effects of xenobiotics, oxygen transfer, and solids separation.

2. Modeling and Kinetics

Dynamic models for activated sludge systems are widely used for design, optimization and control of wastewater treatment systems. Some recent research into activated sludge modeling has focused on modified processes such as membrane bioreactor (MBR), moving bed biofilm reactor (MBBR), and integrated fixed-film activated sludge (IFFAS). A mathematical model for the IFFAS and MBBR processes has been developed [1]. The theoretical basis for the model includes simultaneous diffusion and Monod-type reaction kinetics inside the biofilm. Substrate flux across the biofilm was described with analytical solutions to a 1-dimensional biofilm integrated with an expanded matrix similar to that used for the Activated Sludge Model Number 2D (ASM2d). The steady-state model represents a continuous flow, stirred tank reactor. Sen and Randall [2-4] developed a computational model (AQUIFAS) for activated sludge, IFFAS, and MBBR systems. The model uses a biofilm model embedded in a multi cell activated sludge model. AQUIFAS can be used to compute the biofilm thickness and the impact of biofilm thickness on performance. It can also provide information to create a table of biofilm yields at different substrate concentrations. Lubello *et al.* [5] present a modified version of the ASM1 model, designated ASM-S. The ASM-S correctly simulated solids production over a wide range of solids retention time for two pilot scale MBR systems. Based on experimental results, it appears that solids production may be suitably estimated using the ASM-S. The ASM-S incorporates a hydrolysis kinetic process which affects the biomass fractions X_i and X_p. These fractions are assumed to be inert in the traditional ASM1. Jiang *et al.* [6] modeled a laboratory scale MBR using the ASM2d. They reported that the ASM2d could be used for the MBR under certain conditions. These included use of a lower maximum specific growth rate for the MBR nitrifiers and a greater biomass affinity to oxygen and ammonia.

A sequencing batch reactor (SBR) operates by exposing microbes to high substrate concentrations for a relatively short time period. Alongside SBRs, internal storage of organic polymers by the microbes under high loading conditions is a major removal mechanism for biodegradable carbon. A new kinetic model was developed to describe the microbial polymer storage process under anoxic conditions in activated sludge [7]. The model uses a kinetic approach to describe how microbes accumulate degradable organic carbon in the form of internally stored polymers. The model was compared with ASM1 and ASM3 and results show that the kinetic mass transport model was better able to describe the microbial storage processes under anoxic conditions. Yoshida *et al*. [8] modified ASM2d to evaluate nitrite inhibition of poly-phosphate (poly-P) accumulating organisms (PAOs) by including the assumed intracellular reaction product of nitrite. The modified model named "Nitrite-Complex Model" incorporates new terms for nitrite (SNO2) and reaction complex (Xcomplex) into ASM2d. The new model was able to fit the measured phosphate (P) concentration both when nitrite was present in the system and when it disappeared from the system. Alasino *et al.* [9] extended the ASM3 with the Bio-P module for computing biological P removal and used it to study the reaction compartments and the Takács model for representing secondary settling. The optimization model was solved with a General Algebraic Modeling System and optimal configurations and designs were reported for case studies. The model was sufficiently robust to solve efficiency scenarios having a broad range of operational conditions.

Tannins are a class of polyphenols that commonly occur in wastewater due to the natural breakdown of plant matter. Activated sludge treatment of simulated wastewater containing tannic acid was investigated to find the optimal biodegradation conditions and investigate aerobic biodegradation kinetics [10]. A biodegradation kinetic model that considers substrate inhibition and endogenous decay was developed. The kinetic parameters μ_{max}, K_s, K_I, K_d and Y for the model were estimated at 0.208 h^{-1}, 226 mg/L, 522 mg/L, 0.0092 h^{-1} and 0.594 respectively. Pai *et al.* [11] introduced a new modeling concept to evaluate the effects of cadmium and copper on the heterotrophic growth rate constant (μH) and lysis rate constant (bH) for activated sludge. The kinetic model indicated that the inhibitory effect on μH and the enhancement effect on bH should be considered when heavy metals are present. Hiatt *et al.* [12] evaluated the Activated Sludge Model for Nitrogen (ASMN) by doing steady-state and dynamic simulations with a wastewater containing high COD and nitrogen (N) concentrations and an inhibitor for ammonia-oxidizing bacteria. The wastewater treatment simulations were conducted under a wide range of operating conditions. The pH and temperature were found to be the major factors influencing nitrification performance under upset and startup conditions. Patziger *et al.* [13] describe a novel mass transport model for activated sludge which involves a 2-dimensional secondary settling tank model coupled with a mixed reactor model of the bioreactor. The model is capable of evaluating different sludge return strategies and their influence on the sludge balance of the activated sludge system. Results from an investigation of a peak flow event at the Graz WWTP are discussed. Abusam and Keesman [14] developed a dynamic model of the sludge consolidation processes in secondary settling tanks and incorporated it into the double exponential settling model. The modified double exponential model was calibrated and validated with data from a full-scale wastewater treatment plant. The validity of the model was confirmed by good agreement between predicted and measured data.

3. Process Microbiology

Biodegradation of azo dyes under anaerobic conditions can generate aromatic amines. Metabolites from aromatic amines can be resistant to further biodegradation and exhibit toxicity to aquatic organisms. Research was done to develop a biological treatment process for 4-nitroaniline [15]. Three bacteria identified as *Acinetobacter sp., Citrobacter freundii and Klebsiella oxytoca* were isolated from enrichment cultures on 4-nitroaniline and mixed cultures were studied to determine optimal conditions for biodegradation. Findings showed that enrichment cultures from activated sludge can effectively remove dyes and their toxic intermediates, and that treatment may best be accomplished using an anaerobic-aerobic process. Van Leeuwen *et al.* [16] operated two bench-top activated sludge processes with a synthetic wastewater prepared with typical biodegradable substances plus methylene blue at 5 mg/L. Ozone was applied continuously and directly to one of the processes at 17 mg/L based on inflow rate. The methylene blue was reduced by 95% in the ozonated process compared with just 40% in the non-ozonated control. Wang *et al.* [17] conducted batch experiments to study the biodegradation of 2-methylquinoline in activated sludge. Results indicated that 2-methylquinoline was degraded under both aerobic and denitrifying conditions, but degradation was significantly faster under aerobic conditions. Analysis determined that 1,2,3,4-tetrahydro-2-methylquinoline, N,N-diethyl-benzenamine and 4-ethyl-benzenamine were common metabolites. 1,2,3,4-tetrahydro-2-methylquinoline was detected in the final effluent under both conditions.

Room temperature ionic liquids (RTILs) are organic salts with melting points less than 100 °C. RTILs are being considered as replacements for a range of different volatile organic compounds used in industrial processes. Toxicity assays for some RTILs used in the chemical process industry were conducted [18]. Three bacterial-based toxicity assays were done with several imidazolium-derived compounds as well as the precursor compound 1-methylimidazole. Shk1 and Microtox assays were used as surrogate assays for RTIL toxicity to bacterial respiration in activated sludge. A respirometry assay procedure was also used to directly measure RTIL toxicity on mixed bacterial culture. The Shk1 EC_{50} values for the RTIL compounds studied ranged from 841 mg/L to 2,060 mg/L. These values were higher, *i.e.*, less toxic, than Shk1 EC_{50} values reported for aromatic solvents such as para-xylene (51 mg/L), toluene (93 mg/L), and benzene (202 mg/L). Luongo and Zhang [19] studied the toxicity of carbon nanotubes (CNTs) on wastewater treatment facilities. The impact of increased commercial CNT utilization on treatment facilities is currently unknown. An activated sludge respiration inhibition test was used to study the effects of CNTs on sheared and unsheared mixed liquor. Greater respiration inhibition was observed for the sheared mixed liquor and the inhibition was found to be dose dependent. Several interesting images of CNTs incorporated into mixed liquor obtained with scanning electron microscopy are included. Liang *et al.* [20] investigated the inhibitory effects of silver nanoparticles (AgNPs) in wastewater treatment plants. Bacterial responses to shock loading of AgNPs were determined by observing changes in effluent quality, respirometric assays, and microbial community structure analysis. The study concluded that at a total Ag concentration of 1 mg/L, the AgNPs inhibited the nitrifying activated sludge by 41.4% as compared to only 13.5% inhibition for ionic silver at the same concentration.

A molecular-based viability assay can be a tool for optimizing useful microbial populations in wastewater treatment and for monitoring potentially pathogenic bacteria. Gedalanga and Olson [21] used Ethidium monoazide bromide (EMA) with pure cultures and environmental waters at low concentrations (1.0–7.5 μg/mL) for enumeration of viable and viable but nonculturable *Escherichia coli*. EMA treatment was not effective in primary clarifier and secondary trickling filter effluents where turbidities were ≥10 NTU. Results indicate that EMA can be used in routine quantitative polymerase chain reaction amplification assays, but optimum conditions for exposure must be identified for each sample type due to sample matrix effects such as turbidity. Foladori *et al.* [22] proposed a rapid procedure using flow cytometry and potentially amenable to automation for quantifying viable and active bacteria cells, estimating their biovolume, and calculating their biomass in the main stages of a wastewater treatment plant. The procedure was used to calculate the viable and active bacterial mass in wastewater, activated sludge, and effluent expressed as VSS or particulate COD. Results indicated that viable bacterial biomass composed 4.8% of the particulate COD in the raw wastewater, 10.7% in the settled wastewater, 11.1% in the activated sludge, and 3.2% in the effluent. Baek and Pagilla [23] studied the microbial community structures of conventional activated sludge and MBR systems treating municipal wastewater using Fluorescent in-situ Hybridization (FISH) analysis to identify differences. FISH is a molecular probe procedure that uses labeled DNA to quantify specific types of RNA in the microbial population. The presence of certain types of RNA in the sludge can indicate differences in the activity of various groups of bacteria. Results generally indicated that the MBR biomass could be less active than conventional activated sludge biomass due to higher solids retention time (SRT). However the MBR retained more active autotrophic biomass compared to conventional activated sludge and therefore more ammonia removal could occur in the MBR. Felföldi *et al.* [24] assessed the microbial community of a lab-scale activated sludge system treating coke plant wastewater. Both cultivation-based and culture-independent techniques were used for the assay. Results showed that the microbial community was dominated by easily cultured heterotrophic bacteria. *Comamonas badia* was identified as the predominant member of the bacterial community. The phenol degradation capability of numerous strains of bacteria in the community were determined, some strains were able to degrade phenol at elevated concentrations up to 1,500 mg/L. You *et al.* [25] determined that ammonia-oxidizing archaea (AOA) were found to thrive in wastewater treatment systems, where they may outnumber their counterpart, ammonia-oxidizing bacteria (AOB) in systems operated at high SRT and low dissolved oxygen levels. The presence of AOA in activated sludge presents opportunities for studying its ammonia removal role in wastewater treatment plants and wetlands.

4. Nitrogen and Phosphorus Removal

Removal of ammonia, nitrate, and nitrite is an important goal for many wastewater treatment plants. Biologically mediated removal of N compounds usually requires that treatment systems be operated with high SRT. If it is not feasible to operate at high SRT, an alternative may be to add biofilm attachment surfaces to the system. The performance of the hybrid membrane biofilm process (HMBP) was studied under a range of BOD and ammonium loads and the dominant mechanisms of N removal were determined [26]. For the HMBP, it was concluded that nitrate is the main product of nitrification, nitrification rates are not sensitive to BOD loadings, and full denitrification occurred when influent BOD concentrations were sufficiently high. González *et al.* [27] studied the performance of activated sludge using a pre-denitrification configuration treating swine waste slurry at a hydraulic detention time of 7.7 days. The reactor was fed swine slurry containing 19, 2.6, and 0.27 g/L of total COD, total Kjeldhal N, and soluble P, respectively. N removal displayed a clear dependence on the feed composition. Zheng *et al.* [28] compared the use of alkaline fermentation liquid from waste activated sludge to acetic acid as the major carbon source for P and N removal using anaerobic followed by alternating aerobic-anoxic conditions. Results indicated that ammonium was completely removed with either alkaline fermentation liquid or acetic acid as the carbon source. However using alkaline fermentation liquid resulted in higher removals for P (95%) and N (82%), while using acetic acid produced lower removals (87% and 74%, respectively). Lee *et al.* [29] operated a lab-scale UCT-type MBR for simultaneous biological N and P removal. The MBR was evaluated with high-strength and low-strength wastewater feed. Results showed that N and P removal was achieved with the high-strength wastewater feed, and that N and P removal decreased with the low-strength feed probably due to limited organic content. Sludge production of the UTC-type MBR was similar to conventional activated sludge.

Cyclic activated sludge technology (CAST) is a type of SBR. CAST is considered to be an effective nutrient removal process especially for small wastewater treatment plants. Ma *et al.* [30] used a bench-scale CAST system to study P removal. A series of batch tests were carried out to demonstrate the buildup of denitrifying polyP-accumulating organisms in the CAST system. A step-feed CAST with sufficient influent carbon sources had the highest N and P removal efficiency and good sludge settling. The average reduction rates of COD, $NH4^{+}$-N, $PO4^{3-}$-P and total N were 88.2%, 98.7%, 97.5% and 92.1%, respectively. Machnicka *et al.* [31] confirmed that filamentous bacteria have the ability to take up P and accumulate polyP. Hydrodynamic disintegration of foam microorganisms results in the movement of P, metal cations, and ammonium-N into the liquid phase and foam disintegration allows the removal of part of the nutrients in the form of struvite. Manyumba *et al.* [32] evaluated two pilot-scale biological nutrient removal processes, the Johannesburg (JHB) process and a combined JHB and five-stage Bardenpho process, over a 2 year period to assess the effect of sewage strength on bio-P removal. The JHB averaged effluent total-P of 2.4 mg/L and the JHB and five-stage process in combination averaged 1.4 mg/L effluent total-P. Process performance was improved by dosing the influent with acetate. Lee and Bishop [33] measured P concentration microprofiles in activated sludge flocs in the enhanced biological phosphate removal process (EBPR), and conducted an in situ fluorescent hybridization and clone library analysis to indentify polyP accumulating organisms. Microprofiles indicated that the P concentration increased moving toward the center of the floc and that the floc centers had the highest P concentration. It was assumed that P was not consumed by microbes and that transfer from the floc to the bulk liquid was diffusion limited. The effective P release diffusion constant within the flocs was calculated to be 3.33×10^{-7} cm^2/s at the end of the anaerobic portion of the EBPR process.

5. Treatment and Effects of Xenobiotics

Certain chemicals which are not normally produced by wastewater treatment organisms but are sometimes present in microbes found in the wastewater treatment system are termed xenobiotics. Pharmaceutical compounds are a group of xenobiotics that has received much attention recently. For example, the spread of antibiotic resistant bacteria and genes is considered to be a significant emerging public health issue. The propensity of activated sludge processes at three wastewater treatment plants to amplify or attenuate tetracycline resistant bacteria and tetracycline resistant genes was studied by Kim *et al.* [34]. The results indicate that wastewater treatment processes are significant point sources of tetracycline resistance determinants to the environment. A mathematical basis to compute the production capacity of these determinants in the activated sludge process is provided. Lefkowitz and Duran [35] investigated changes in antibiotic resistance of *Escherichia coli* in different stages of conventional domestic wastewater treatment. More than 3500 *E. coli* isolates from the wastewater treatment process were tested for resistance to six different antibiotics. When comparing different stages within samples, there seemed to be an increase in resistance to ampicillin and amoxicillin between the raw influent and primary effluent. In addition, the percent of isolates with multiple antibiotic resistances increased through the treatment process. Plósz *et al.* [36] discuss a process model for an activated sludge treatment system to predict the removal of the antibiotics sulfamethoxazole, tetracycline, and ciprofloxacin. Compound removal was observed and a model was developed using simulation software. Results suggests that robust model prediction can be produced by estimating the influent chemical load being biodegraded by a given parent compound, e.g., human conjugates, as an antibiotic mass that is proportional to the load of the parent compound. Zhang *et al.* [37] discuss removal mechanisms and efficiencies for carbamazepine and diclofenac in wastewater treatment plants. The presence of both drugs was examined in plant effluents, surface waters, groundwater, and drinking water. It was determined that the removal efficiency for carbamazepine resulting from wastewater treatment was generally less than 10% and for diclofenac it varied between 0% and 80%. Ecotoxicological studies of both drugs indicate that they do not readily cause acute toxic effects at environmental concentrations, but that their chronic effects may warrant cautious attention. Helbling *et al.* [38] developed an efficient procedure for high-throughput elucidation of transformation products (TPs) for xenobiotics undergoing microbially mediated transformation. Six pharmaceuticals and six pesticides were spiked individually into batch reactors seeded with activated sludge. Previously unreported microbial TPs were identified for the pharmaceuticals bezafibrate, diazepam, levetiracetam, oseltamivir, and valsartan, and results indicated that the combined use of the target and non-target screening methods produced a better interpretation of the TPs generated. Chong [39] developed a mathematical model for degrader formation by conversion of indigenous microbial cells. The model formulated the lag and degrader formation using the sigmoid function and growth with Haldane kinetics. Accumulation and degradation experiments were conducted using 2,4-D as the target compound in batch type shake-flask reactors. The model was used to match the experimental outcome and to evaluate the parameters for the accumulation function and the degradation kinetics. The study concludes that the model serves the need for a rational representation of microbial acclimation to a xenobiotic.

6. Oxygen Transfer

Understanding oxygen transfer in the activated sludge process is essential for the proper design and operation of wastewater treatment plants. The effect of SRT and the mixed liquid volatile suspended solids concentration (MLVSS) on oxygen transfer in activated sludge and the mass transfer coefficient (k_{La}) was studied in a pilot-scale MBR treating synthetic greywater [40]. Results indicated that the α-factor, *i.e.*, the ratio of oxygen transfer coefficients for wastewater and clean water, was reduced when free water content decreased and floc volume increased and that a reduction of oxygen transfer was observed with increasing MLVSS concentration. It was also concluded that when floc volume does not change, the oxygen transfer increases as the SRT increases. Gillot and Héduit [41] examined the effects of different geometric and operating parameters on the α-factor for fine bubble aerators equipped with EPDM membrane diffusers. Measurements were taken at nitrifying plants operating under extended aeration and treating mainly domestic wastewater. Measurements from 14 nitrifying plants with very low F/M ratios indicated that α-factor ranged between 0.44 and 0.98. A new composite variable (the Equivalent Contact Time, ECT) was defined which makes it possible for a specific aeration tank to predict the α-factor knowing the SRT, the clean water oxygen transfer coefficient, and the supplied air flow. Almoustafa *et al.* [42] discussed the use of a down-flow, gas-liquid contactor for oxygen transfer into activated sludge. The mass transfer efficiency was evaluated by measuring k_{La} in clean water and in activated sludge. k_{La} values obtained in clean water were compared to values obtained in sludge, enabling an assessment of the α-factor. The α-factor determined was about 0.5 for the range of liquid flow rates used. Iversen *et al.* [43] present experimental findings regarding the influence of 13 flux enhancing chemicals (FEC) including FeCl3, polyaluminum chloride, 2 chitosans, 5 synthetic polymers, 2 starches and 2 activated carbons on respirometric characteristics and nitrification/denitrification performance of mixed liquor from an MBR. FEC have potential for reducing membrane fouling in the MBR. Results show that changes in k_{La} values were mostly not significant. However, many of the FEC did produce negative effects on the operation of the MBR. For example, use of polyaluminum chloride reduced the nitrification rate (−16%), the denitrification rate (−43%), and the oxygen transfer (−13%) in the mixed liquor. Rosso *et al.* [44] summarize their 30 years of experience in aeration research. Results obtained from tests on clean- and process-water demonstrate the benefit for aeration of operating at a high SRT, the benefit of using nutrient-removing selectors to sorb and utilize substrate which could accumulate at bubble surfaces and decrease aeration efficiency, and the reduction of aeration efficiency caused by dissolved surfactants. Jin *et al.* [45] treated high concentration pesticide wastewater with a pressurized activated sludge process. The COD loading rates in the pressurized system ranged from 5.8 to 7.6 kg COD /m^3 day compared to 2.0 to 2.8 kg COD/m^3 day for the non pressurized system. Results showed that removal of COD increased steadily with increased operating pressure, aeration time, and sludge concentration. The optimal aeration time was 6 to 8 hours at a pressure of 0.3 MPa. Jolly *et al.* [46] carried out oxygen transfer tests to demonstrate the efficiency of a new, cost effective, fine bubble diffuser for wastewater aeration systems. These diffusers are configured in mats or panels and are attached to the floor of the tank rather than the side. The results are compared with tests carried out on other types of diffusers. Present capital and net present costs for various diffuser installations are discussed.

7. Solids Separation

Stable and effective capture, recycle and removal of biological solids produced in activated sludge systems are crucial for proper system operation. Seven cationic polyelectrolytes were tested as additives to improve the settling of aeration tank effluent from a full-scale wastewater treatment plant [47]. The additives were evaluated based on their settling curves and zone settling velocities. Results indicated that the additives produced reduced lag-times, greater descending speed of the sludge-water interface, greater descending distance, and lower sludge volume indices. Wilén *et al.* [48] studied activated sludge floc composition, flocculation, and settling properties at a full scale plant over two years. The following observations were made: (1) that the protein content of the sludge and extracellular polymeric substances increased significantly during the winter and coincided with higher suspended solids concentrations in the effluent and increased shear sensitivity of the flocs, (2) that high iron concentrations in sludge used to precipitate P were found to have a negative impact on the settling and compaction properties of the sludge and a positive impact on floc stability, and (3) that higher organic loading improved sludge settling and compaction. Jones and Schuler [49] monitored four full-scale activated sludge systems for biomass density, filament content, and settleability for one year. Results indicated that biomass density in all plants was significantly higher in warm weather than in cold weather, settleability was significantly worse in cold weather in three of the plants, and the inverse of the buoyant density was correlated with settleability in the same three plants. The results suggest that variable density plays a role in seasonally variable settleability in some full-scale treatment plants.

8. Discussion

The activated sludge process is the most widely used biological wastewater treatment process. Activated sludge plants are successfully operated in many different climates and at a broad range of elevations. The plants vary in size from single household package plants to huge plants serving entire cities. The process configuration can vary from a relatively simple complete mix process to highly sophisticated processes such as integrated fixed-film activated sludge.

Considering the extensive use of the activated sludge process, it is not surprising that a tremendous amount of research has been done on this topic in recent years. This paper seeks to review some of the research publications relating to this treatment process published in 2007, 2008 and 2010. The review specifically focuses on the topics of modeling and kinetics; process microbiology; nitrogen and phosphorus removal; treatment and effects of xenobiotics; oxygen transfer; and solids separation.

In the area of modeling and kinetics, several researchers applied modified versions of ASM1 and ASM2d to model developing activated sludge processes such as MBR, MBBR, IFFAS, and SBR. Modeling studies were also done to better simulate removals of nitrogen and phosphorus compounds, to study substrate inhibition, and to understand process sludge balance. These studies indicate that the established models are continuously being refined and expanded to better simulate specific aspects of the activated sludge process. The microbiology of the activated sludge process is being studied to enhance biodegradation of resistant organic compounds and understand inhibition of microbial respiration caused by organic and inorganic compounds. Research was also done to develop improved methods for studying wastewater treatment microbial populations. With the introduction of new manufacturing processes and associated waste products, the study of treatment microbiology has become a very active research area. N and P removal by the activated sludge process has long been used as a means of controlling unwanted nutrient discharges. Recent research has mainly focused on the removal efficiencies of developing process modifications such as HMBP, MBR, CAST and EBPR. In general, the processes operated for these research studies demonstrated relatively high (*i.e.*, 82% to 99%) removal efficiencies for N and P. The study of xenobiotics in wastewater treatment is a research area that has attracted much interest in recent years. Xenobiotics such as pharmaceutical compounds can enter the activated sludge system with the wastewater and cause concerns with the spread of antibiotic-resistant bacteria and genes. Research on this topic promises to expand as the quantities and diversity of pharmaceutical chemicals being used increases. Effective oxygen transfer and solids separation are both necessary for proper operation of activated sludge systems. Recent research related to oxygen transfer has studied transfer rates achieved with modified processes such as MBR and with new air diffuser designs. Solids separation research has indicated that solids tend to settle better in the summer compared to winter and that this difference may be related to higher sludge density in summer and higher sludge content of protein and extracellular polymeric substances in the winter.

9. Conclusions

Activated sludge wastewater treatment continues to draw significant research attention. Much of the recent activity has focused on evaluating various process modifications designed to increase treatment efficiency. A very diverse set of tools are being used for this research including computer modeling, bench and pilot scale studies, physical/chemical analyses, and microbiological and genetic investigations.

References

1. Boltz, J.P.; Johnson, B.R.; Daigger, G.T.; Sandino, J. Modeling integrated fixed-film activated sludge and moving-bed biofilm reactor systems I: Mathematical treatment and model development. *Water. Environ. Res*. **2009**, *81*, 555-575.
2. Sen, D.; Randall, C.W. Improved computational model (AQUIFAS) for activated sludge, integrated fixed-film activated sludge, and moving-bed biofilm reactor systems, Part I: Semi-empirical model development. *Water Environ. Res*. **2008**, *80*, 439-453.
3. Sen, D.; Randall, C.W. Improved computational model (AQUIFAS) for activated sludge, integrated fixed-film activated sludge, and moving-bed biofilm reactor systems, Part II: Multilayer biofilm diffusional model. *Water Environ. Res*. **2008**, *80*, 624-632.
4. Sen, D.; Randall, C.W. Improved computational model (AQUIFAS) for activated sludge, integrated fixed-film activated sludge, and moving-bed biofilm reactor systems, Part III: Analysis and verification. *Water Environ. Res*. **2008**, *80*, 633-646.
5. Lubello, C.; Caffaz, S.; Gori, R.; Munz, G.A. Modified activated sludge model to estimate solids production at low and high solids retention time. *Water Res*. **2009**, *43*, 4539-4548.
6. Jiang, T.; Sin, G.; Spanjers, H.; Nopens, I.; Kennedy, M.; Van Der Meer, W.; Futselaar, H.; Amy, G.; Vanrolleghem, P. Comparison of modeling approach between membrane bioreactor and conventional activated sludge process. *Water Environ. Res.* **2009**, *81*, 432-440.
7. Ni, B.; Yu, H. Kinetic modeling microbial storage process in activated sludge under anoxic conditions. *Chem. Engr. Sci*., **2008**, *63*, 2785-2792.
8. Yoshida, Y.; Kim, Y.; Saito, T.; Tanaka, K. Development of the modified activated sludge model describing nitrite inhibition of aerobic phosphate uptake. *Water Sci. Technol*. **2009**, *59*, 621-630.
9. Alasino, N.; Mussati, M.; Scenna, N.; Aguirre, P. Wastewater treatment plant synthesis and design: Combined biological nitrogen and phosphorus removal. *Ind. Eng. Chem. Res.* **2010**, *49*, 8601-8612.
10. Li, W.W.; Li, X.D.; Zeng, K.M. Aerobic biodegradation kinetics of tannic acid in activated sludge system. *Biochem. Eng. J.* **2009**, *43*, 142-148.
11. Pai, T.Y.; Wang, S.C.; Lo, H.M.; Chiang, C.F.; Liu, M.H.; Chiou, R.J.; Chen, W.Y.; Hung, P.S.; Liao, W.C.; Leu, H.G. Novel modeling concept for evaluating the effects of cadmium and copper on heterotrophic growth and lysis rates in activated sludge process. *J. Hazard. Mater.* **2009**, *166*, 200-206.
12. Hiatt, W.; Grady, C.; Leslie, C. Application of the activated sludge model for nitrogen to elevated nitrogen conditions. *Water Environ. Res.* **2008**, *80*, 2134-2144.
13. Patziger, M.; Kainz, H.; Hunze, M.; Józsa, J. Analysing sludge balance in activated sludge systems with a novel mass transport model. *Water Sci. Technol*. **2008**, *57*, 1413-1419.
14. Abusam, A.; Keesman, K. Dynamic modeling of sludge compaction and consolidation processes in wastewater secondary settling tanks. *Water Environ. Res.* **2009**, *81*, 51-56.
15. Khalid, A.; Arshad, M.; Crowley, D. Biodegradation potential of pure and mixed bacterial cultures for removal of 4-nitroaniline from textile dye wastewater. *Water Res.* **2009**, *43*, 1110-1116.

16. Van Leeuwen, J.; Sridhar, A.; Harrata, K.; Esplugas, M.; Onuki, S.; Cai, L.; Koziel, J. Improving the biodegradation of organic pollutants with ozonation during biological wastewater treatment. *Ozone: Sci. Eng.* **2009**, *31*, 63-70.
17. Wang, W.; Li, Y. Biodegradation and metabolites of 2-methylquinoline by acclimated activated sludge under aerobic and denitrifying conditions. *Process Biochem*. **2010**, *45*, 919-928.
18. Azimova, M.; Morton, S.; Frymier, P. Comparison of three bacterial toxicity assays for imidazolium-derived ionic liquids. *J. Environ. Eng.* **2009**, *135*, 1388-1392.
19. Luongo, L.; Zhang, X. Toxicity of carbon nanotubes to the activated sludge process. *J. Hazard. Mater.* **2010**, *178*, 356-362.
20. Liang, Z.; Das, A.; Hu, Z. Bacterial response to a shock load of nanosilver in an activated sludge treatment system. *Water Res*. **2010**, *44*, 5432-5438.
21. Gedalanga, P.; Olson, B. Development of a quantitative PCR method to differentiate between viable and nonviable bacteria in environmental water samples. *Appl. Microbiol. Biotechnol.* **2009**, *82*, 587-596.
22. Foladori, P.; Bruni, L.; Tamburini, S.; Ziglio, G. Direct quantification of bacterial biomass in influent, effluent and activated sludge of wastewater treatment plants by using flow cytometry. *Water Res.* **2010**, *44*, 3807-3818.
23. Baek, S.; Pagilla, K. Microbial community structures in conventional activated sludge system and membrane bioreactor (MBR). *Biotech. Bioprocess Eng*. **2009**, *14*, 848-853.
24. Felföldi, T.; Székely, A.; Gorál, R.; Barkás, K.; Scheirich, G.; András, J.; Rácz, A.; Márialigeti, K. Polyphasic bacterial community analysis of an aerobic activated sludge removing phenols and thiocyanate from coke plant effluent. *Bioresour. Technol*. **2010**, *101*, 3406-3414.
25. You, J.; Das, A.; Dolan, E.; Hu, Z. Ammonia-oxidizing archaea involved in nitrogen removal. *Water Res.* **2009**, *43*, 1801-1809.
26. Downing, L.; Nerenberg, R. Total nitrogen removal in a hybrid, membrane-aerated activated sludge process. *Water Res.* **2008**, *42*, 3697-3708.
27. González, C.; García, P.; Muñoz, R. Effect of feed characteristics on the organic matter, nitrogen and phosphorus removal in an activated sludge system treating piggery slurry. *Water Sci. Technol.* **2009**, *60*, 2145-2152.
28. Zheng, X.; Chen, Y.; Liu, C. Waste activated sludge alkaline fermentation liquid as carbon source for biological nutrients removal in anaerobic followed by alternating aerobic-anoxic sequencing batch reactors. *Chin. J. Chem. Eng.* **2010**, *18*, 478-485.
29. Lee, H.; Han, J.; Yun, Z. Biological nitrogen and phosphorus removal in UCT-Type MBR process. *Water Sci. Technol.* **2009**, *59*, 2093-2099.
30. Ma, J.; Peng, Y.; Wang, S.; Wang, L.; Liu, Y.; Ma, N. Denitrifying phosphorus removal in a step-feed CAST with alternating anoxic-oxic operational strategy. *J. Environ. Sci.* **2009**, *21*, 1169-1174.
31. Machnicka, A.; Grubel, K.; Suschka, J. Enhanced biological phosphorus removal and recovery. *Water Environ. Res.* **2008**, *80*, 617-623.
32. Manyumba, F.; Wood, E.; Horan, N. Meeting the phosphorus consent with biological nutrient removal under UK winter conditions. *Water Environ. J.* **2008**, *23*, 83-90.

33. Lee, W.; Bishop, P. In situ microscale analyses of activated sludge flocs in the enhanced biological phosphate removal process by the use of micro electrodes and fluorescent in situ hybridization. *J. Environ. Engr.*, **2010**, *136*, 561-567.
34. Kim, S.; Park, H.; Chandran, K. Propensity of activated sludge to amplify or attenuate tetracycline resistance genes and tetracycline resistant bacteria: A mathematical modeling approach. *Chemosphere* **2010**, *78*, 1071-1077.
35. Lefkowitz, J.; Duran, M. Changes in antibiotic resistance patterns of *escherichia coli* during domestic wastewater treatment. *Water Environ. Res.* **2009**, *81*, 878-885.
36. Plósz, B.; Leknes, H.; Thomas, K. Impacts of competitive inhibition, parent compound formation and partitioning behavior on the removal of antibiotics in municipal wastewater treatment. *Environ. Sci. Technol*. **2010**, *44*, 734-742.
37. Zhang, Y.; Geien S.; Gal, C. Carbamazepine and diclofenac: Removal in wastewater treatment plants and occurrence in water bodies. *Chemosphere* **2008**, *73*, 1151-1161.
38. Helbling, D.; Hollender, J.; Kohler, H.; Singer, H.; Fenner, K. High-throughput identification of microbial transformation products of organic micropollutants. *Environ. Sci. Technol*. **2010**, *44*, 6621-6627.
39. Chong, N. Modeling the acclimation of activated sludge to a xenobiotic. *Bioresour. Technol*. **2009**, *100*, 5750-5756.
40. Henkel, J.; Cornel, P.; Wagner, M. Free water content and sludge retention time: Impact on oxygen transfer in activated sludge. *Environ. Sci. Technol.* **2009**, *43*, 8561-8565.
41. Gillot, S.; Héduit, A. Prediction of alpha factor values for fine pore aeration systems. *Water Sci. Technol.* **2008**, *57*, 1265-1269.
42. Almoustafa, F.; Benadda, B.; Buffière, P. Efficiency of a gas-liquid contactor for the oxygenation of activated sludge: Assessment of mass transfer coefficient. *Chem. Eng. Technol.* **2009**, *32*, 1958-1965.
43. Iversen, V.; Koseoglu, H.; Yigit, N.; Drews, A.; Kitis, M.; Lesjean, B.; Kraume, M. Impacts of membrane flux enhancers on activated sludge respiration and nutrient removal in MBRs. *Water Res.* **2009**, *43*, 822-830.
44. Rosso, D.; Larson, L.; Stenstrom, M. Aeration of large-scale municipal wastewater treatment plants: State of the art. *Water Sci. Technol.* **2008**, *57*, 973-978.
45. Jin, Z.; Pan, Z.; Yu, S.; Lin, C. Experimental study on pressurized activated sludge process for high concentration pesticide wastewater. *J. Environ. Sci.* **2010**, *22*, 1342-1347.
46. Jolly, M.; Green, S.; Wallis-Lage, C.; Buchanan, A. Energy saving in activated sludge plants by the use of more efficient fine bubble diffusers. *Water Environ. J.* **2010**, *24*, 58-64.
47. Al-Jasser, A. Enhancement of sludge settling with chemical additives. *Water Environ. Res.* **2009**, *81*, 849-857.
48. Wilén, B.; Lumley, D.; Mattsson, A.; Mino, T. Relationship between floc composition and flocculation and settling properties studied at a full scale activated sludge plant. *Water Res.*, **2008**, *42*, 4404-4418.

49. Jones, P.; Schuler, A. Seasonal variability of biomass density and activated sludge settleability in full-scale wastewater treatment systems. *Chem. Eng. J.* **2010**, *164*, 16-22.