Treating municipal wastewater with the goal of resource recovery

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ABSTRACT

A new municipal wastewater treatment flowsheet was developed with the objectives of energy sustainability, and water and nutrient recovery. Energy is derived by shunting a large fraction of the organic carbon in the wastewater to an anaerobic digestion system. Aerobic and anaerobic membrane bioreactors play a key role in energy recovery. Phosphorus and nitrogen are removed from the wastewater and recovered through physical-chemical processes. Computer modeling and simulation results together with energy balance calculations, imply the new flowsheet will result in a dramatic reduction in energy usage at lower treatment plant capital costs in comparison to conventional methods.

Key words | municipal wastewater treatment, resource recovery

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INTRODUCTION

A municipal wastewater treatment flowsheet has been developed which achieves the goal of energy sustainability and water and nutrient recovery, while minimizing residual solids production (i.e., biomass) and the release of greenhouse gas (GHG) emissions. This "new flowsheet" integrates uniquely designed biological process systems with physical-chemical unit processes which allows for conversion of the organic carbon in the wastewater to methane, the removal and recovery of phosphorus and nitrogen from the wastewater, and the production of water suitable for reuse. Envirogen Technologies hold the proprietary rights to the new flowsheet concept.

The purpose of this paper is to discuss the treatment principles and mechanisms dictating the performance and operation of the various unit processes making up the new flowsheet embodiment depicted in Figure 1. Examples of attractive, commercially available, systems representing each of the new flowsheet unit processes are presented. Computer modeling and simulation results are used to quantify the advantages of the new flowsheet with respect to energy usage and solids production versus a current conventional approach for treating municipal wastewater with the goal of meeting effluent total suspended solids (TSS), total P and total N requirements of respectively, less than 5, 0.1, and 3 mg/l. Cost information is developed for the two treatment approaches. The paper concludes with a discussion of certain hurdles which must be overcome in order for the new flowsheet to be viewed as attractive.

THE NEW FLOWSHEET

The new flowsheet (Figure 1) is made up of four principal treatment steps namely, an aerobic membrane bioreactor (MBR), a coupled waste solids pretreatment-anaerobic MBR digestion system (anaerobic digestion system), and physical-chemical systems to achieve nutrient removal. The new flowsheet derives energy from the wastewater by first shunting a large fraction (i.e., 75 to 80 percent or more) of the organic carbon in the wastewater to a particulate or solids slurry form and ultimately treating the solids via anaerobic digestion. The organic carbon shunt is maximized in an

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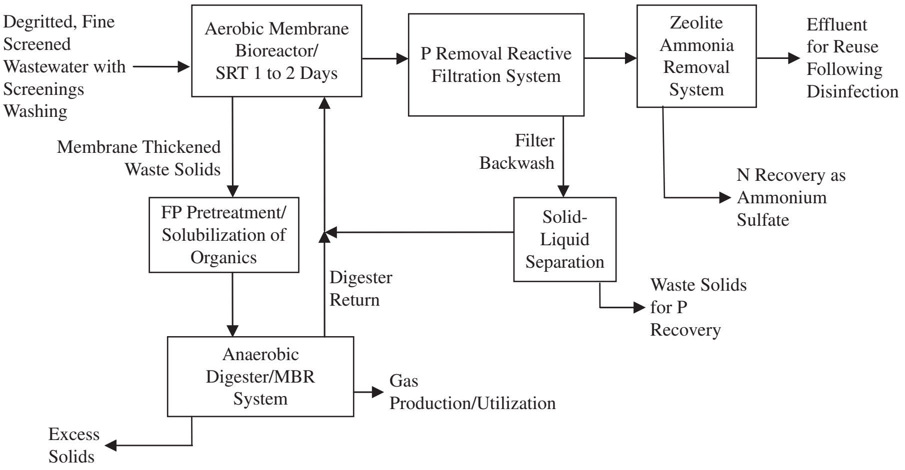

Figure 1 | Simplified schematic representation of the new flowsheet.

efficient fashion through application of the aerobic MBR configuration designed under specific conditions. The new flowsheet accomplishes energy recovery in the form of organic carbon conversion to methane through application of the aerobic MBR configuration and anaerobic digestion. The adsorption-precipitation filtration (i.e., reactive filtration) process (Newcombe *et al.* 2008), represents an attractive alternative to achieve near complete phosphorus removal in the new flowsheet application. The nitrogen in the effluent from the aerobic MBR of the new flowsheet is in the form of ammonia plus a small fraction of soluble organic nitrogen. If near complete nitrogen removal and recovery are the treatment goals, physical-chemical technologies such as ion-exchange and reverse osmosis can be utilized. An analogous approach to ion-exchange referred to as the zeolite ammonia removal (ZAR) process, appears to represent an economical method of accomplishing this goal.

COD removal and energy recovery

Soluble, particulate and colloidal organics, and colloidal inorganics are removed across the aerobic MBR in the new flowsheet. The bioreactor is designed and operated at a low (i.e., 1 to 2 days) solids retention time (SRT) and a high biomass concentration (e.g., 7 g/L measured as volatile suspended solids). The mechanisms responsible for COD removal across the MBR system are:

(1) organic carbon oxidation,
(2) conversion of organic carbon into cell mass,
(3) storage/absorption of organic carbon into the cells,
(4) adsorption of colloidal and/or particulate organic carbon onto the high concentration of total suspended solids (TSS) present in the reactor, and
(5) membrane retention of particulate, colloidal and larger molecular weight soluble organics (i.e., semi-soluble organics).

The last four mechanisms are maximized by the operating conditions maintained in the reactor and choice of the MBR configuration, in turn maximizing the fraction of the wastewater COD that is accumulated and then transferred to the anaerobic step versus the fraction aerobically oxidized to carbon dioxide. The extent of COD accumulation in the aerobic MBR was determined through mathematical modeling using the ASM3 model (Henze *et al.* 2000). This model was selected as it provides flexibility in terms of exploring different mechanisms for increasing COD accumulation. The ASM3 model parameter values reported by Koch *et al.* (2000) were used with the exception of the hydrolysis rate value which was reduced to match the data from a low SRT suspended growth biosystem reported by Frank *et al.* (2008). That data implies at low SRTs there is insufficient time for adsorption, bioflocculation, and hydrolysis of all the particulate and colloidal COD. The results indicate 80 percent of the wastewater COD accumulated in the reactor. Model simulations imply the wastewater characteristics (e.g., total COD, total particulate COD, inert particulate COD, soluble readily biodegradable COD), the COD hydrolysis rate, and limitations with respect to adsorption and bioflocculation are significant factors determining the extent of COD accumulation. These factors and the use of an ultrafiltration membrane based MBR system (i.e., membrane pore size 0.04 μm) may explain the difference in the extent of COD accumulation predicted here versus that observed by others during operation of low SRT suspended growth systems treating a municipal wastewater. Akanyeti *et al.* (2010) operated a laboratory scale, microfiltration membrane based MBR at

SRTs of equal to or less than 1 day and reported COD accumulations in the bioreactor of less than 55 percent. At the Strass full scale plant near Innsbruck, Austria, a conventional suspended growth biosystem operating at an SRT of less than 1 day removed 50 to 54 percent of the wastewater COD, according to a report from Wallis-Lage *et al.* (2009).

The new flowsheet achieves energy recovery through methane generation. In the new flowsheet depicted in Figure 1, thickened waste solids from the aerobic MBR are routed to an anaerobic digestion system operated at mesophilic temperature conditions and consisting of a solids pre-treatment step coupled to an anaerobic MBR. This reactor configuration provides numerous benefits in this application (Sutton *et al.* 2010). The anaerobic MBR is designed around the use of tubular, ultrafiltration membranes. Focused Pulsed (FP) pretreatment is applied to maximize the conversion of the organics to methane and minimize excess solids from the anaerobic MBR system. To minimize the energy required to operate the pretreatment step and the anaerobic MBR, the solids slurry from the aerobic MBR is first thickened. The FP technology uses high voltage electrical micropulses to disrupt the biomass cell wall and membranes, releasing organic material that is more readily bioavailable for methane digestion. Information concerning design and optimization of the anaerobic digestion system is provided elsewhere (Sutton *et al.* 2010).

Nutrient removal and recovery

The reactive filtration process represents an attractive approach to achieve near complete phosphorus removal (i.e., effluent TP less than 0.1 mg/l) and recovery in the new flowsheet application. The process system consists of a continuous backwash filter (CBF) utilizing a reactive filter media (i.e., hydrous ferric oxide coated sand) with a relatively small Fe addition rate (e.g., 12 mg/l). Further details concerning application and modeling of the process system are provided elsewhere (Sutton *et al.* 2009a). The underflow waste solids from the solid-liquid separation step receiving the backwash from the Fe based reactive filtration system (Figure 1), has the potential to represent a slow release, high P containing fertilizer product following dewatering and drying, as discussed elsewhere (Sutton *et al.* 2009b).

The nitrogen to the final treatment step of the new flowsheet is largely in the form of ammonia. The ZAR process appears to represent a technically attractive and economical approach to achieve near complete ammonia removal (i.e., effluent ammonia-N less than 1.5 mg/l) in the new flowsheet application. Ammonia removal is achieved via cation exchange using clinoptilolite preloaded with potassium or hydrogen ions achieved through media regeneration. When potassium sulphate is used as the potassium ion source, nitrogen is recovered in the form of an ammonium sulphate solution representing a fertilizer product. The ZAR system is configured as a downflow submerged media, gravity filter with air-water backwash capability, and provisions to allow the media to soak for a short time (i.e., less than 3 h) to accomplish regeneration after on-line operation for approximately 10 days.

Modeling and model results

A model is under development using the GPS-X wastewater treatment process simulator to help quantify the technical and economic attractiveness of the new flowsheet in the treatment of degritted, fine screened, municipal wastewater. The wastewater characteristics used for the GPS-X simulation are summarized in Table 1. Energy calculations have been added to the model to quantify the energy requirements of the new flowsheet. To-date, only steady-state modeling has been completed and modeling efforts have focused on the treatment steps upstream of the ZAR system. Further details regarding modeling are provided elsewhere (Schraa 2009; Sutton *et al.* 2009b). The energy calculations include the ZAR system.

Table 1 | Characteristics of the wastewater used in GPS-X simulation[a]

Characteristic	Value
Flow rate (m^3/day)	18,925
Temperature (°C)	18
Concentration values (mg/l)	
COD	280
$CBOD_5$	150
TSS	175
VSS	137
TN	30
TKN	30
Soluble TKN	24
NH_4-N	19
TP	6
Soluble TP	5

[a] Characteristics of feed to the aerobic MBR (Figure 1).

Important notes related to modeling of the Figure 1 treatment steps, model results and the energy calculations, follow.

(1) The reactor of the aerobic MBR was modeled as completely-mixed and the ASM3 model was used to model biological growth, as previously discussed. The reactor SRT was set at 1.5 days and a mixed-liquor TSS concentration of approximately 9 g/l was assumed. The resulting reactor hydraulic retention time (HRT) was approximately 0.71 h. It was assumed 15 mg/l of semi-soluble COD was retained by the ultrafiltration membranes. Semi-soluble COD is defined as the COD content of the filtrate after passing through 0.45 μm filter paper. The model results indicate approximately 80 percent of the wastewater COD (Table 1) mass is shunted to the anaerobic digestion system and the COD concentration after the aerobic MBR is 6 mg/l.

(2) The aerobic MBR was designed around the use of a hollow-fiber membrane system manufactured by GE Water & Process Technologies, Oakville, Ontario (GE). The volume of the tank required to house the membranes is approximately equal to that required to operate the tank as the aerobic bioreactor. The tank liquid depth was specified at approximately 4.6 m. At this liquid depth, the coarse bubble aeration required to maximize membrane efficiency translates to an airflow and corresponding oxygen transfer sufficient to meet the bioprocess oxygen requirements. The amount of membrane area contained in the membrane/bioreactor tank is sufficient for operation of the membrane component at a realistic net flux (i.e., approximately 25 l/m^2/h) considering the bioreactor TSS and SRT, the use of a membrane/bioreactor on- off aeration cycle of 10/10 (i.e., 10 seconds on, 10 seconds off), a constant influent flow rate and a temperature of 18 °C. The use of an aeration cycle of 10/10 would normally not be required to achieve the flux stated under the conditions noted, provided the SRT was much higher (e.g., 15 days). The operating membrane area is 30,328 m^2 and the air flow is approximately 160 m^3/min at standard conditions.

(3) A membrane separator was used to achieve thickening of the waste solids from the aerobic MBR (Figure 1). It was assumed the solids would be thickened to a TSS concentration of 40 g/l using hollow-fiber membranes. This membrane step and those associated with the aerobic and anaerobic MBRs, were modeled using a membrane filter model. The operating membrane area was 3032 m^2.

(4) A customized mass balance model was used for the digester pretreatment step based on application of the FP technology. The MantisAD biological model was used for the anaerobic MBR digester with certain additions to account for phosphorus release and uptake due to biomass growth, and the effect of the FP pretreatment step. It was assumed 500 mg/l of semi-soluble COD was retained by the membrane and directed to the waste solids. The tubular membrane system was designed assuming an average flux of 51 l/m^2/h. On the basis of achieving 85 percent conversion of the COD in the thickened feed solids to methane, model results indicate the optimal anaerobic digestion system (Sutton *et al.* 2010) consists of anaerobic MBRs designed at an SRT of 43 days and a mixed-liquor TSS concentration of approximately 40 g/l. The resulting reactor HRT is 15.0 days. The ratio of recycle from the anaerobic MBRs to the FP step feed flow is 0.33. The amount of excess solids from the anaerobic digestion system (Figure 1) requiring disposal is 1200 kg/day.

(5) The phosphorus removal reactive filtration system model is comprised of mass balances on the COD, inorganic suspended solids, metal precipitates, nitrogen, and phosphorus water quality variables used in the ASM3 biological model with metal precipitates and phosphorus variables having been added to the model. An empirical expression was used within the mass balances to predict the filtration of particulates, and a steady-state version of the ASM2d chemical precipitation model was used to model the adsorption and co-precipitation of dissolved phosphorus. The Fe addition rate to the reactive filtration system was set at 12 mg/l.

(6) The ZAR system gravity filters are designed at a hydraulic loading rate of approximately 4.7 m/h. The operating clinoptilolite media volume is 153 m^3.

(7) Energy balance calculations associated with the digester tank of the anaerobic MBR are comparable to those associated with a conventional digester with modifications to account for the effect of the pretreatment step and its configuration as an MBR. Energy requirements for the other new flowsheet treatment steps were based on input provided by the system suppliers.

COMPARISON OF NEW FLOWSHEET AND CONVENTIONAL FLOWSHEET

In order to quantify the advantages of the new flowsheet, design and cost information was developed for a conventional approach to meet the effluent requirement stated in the section entitled, "INTRODUCTION". The conventional approach was an MBR based biological nutrient removal (BNR) system without primary treatment. Aerobic digestion, typically used at smaller municipal treatment plants, was assumed for waste solids stabilization. The major process and system design characteristics of the steps making up the conventional flowsheet are as follows.

- The BNR configuration consists of sequential anoxic, aerobic and post-anoxic stages followed by a membrane tank. A recycle ratio of four is assumed for return of mixed-liquor from the membrane tank to the first stage anaerobic tank. The return flow passes through an anoxic tank prior to introduction to the anaerobic stage. The BNR system is designed at a total SRT of 15 days with TSS and VSS concentrations in the anaerobic, anoxic and aerobic

Table 2 | New flowsheet and conventional flowsheet energy balance results[a]

	Energy produced or required, kWh/day	
Energy value	**New flowsheet**	**Conventional flowsheet**
Thermal Energy		
Recovered From Digester Gas	+5860	–
Required For Waste Solids Heating[b]	−377	–
Energy Balance	+5484	–
Electrical Energy		
Recovered From Digester Gas	+4100	–
Influent/Headworks Pumping	−1131	−1131
Aerobic MBR Membrane System Aeration	−3500	−1750
Aerobic MBR Permeate Extraction & Other Energy Needs[c]	−835	−835
BNR System Aeration	–	−2715
BNR System Mixing	−516	−1018
Reactive Filtration CBFs[d]	−3	–
ZAR System	–	–
Aerobic Digester Aeration	−325	−1884
Waste Solids Thickening	−1653	–
Digester Pretreatment Step Operation	−600	–
Digester/MBR Membrane Operation	−125	–
Digester Mixing	−878	–
Interstage Pumping[e]	−46	−2827
Excess Solids Centrifugation[f]	−5512	−75
Energy Balance		−12,235
Total Energy Balance[b]	−28	−12,235

[a] Total Energy Balance results assume all energy can be utilized with 28 percent converted to electrical and 40 percent converted to thermal (i.e., 68 percent energy recovery using microturbine).

[b] Includes heat loss through digester walls, roof and floor.

[c] Includes permeate extraction, air compressor, chemical pumping, controls, etc.

[d] Includes air compressor for airlift pumping and chemical pumping.

[e] Includes feed and recycle pumping to and around systems downstream of headworks.

[f] Centrifugation of solids from either anaerobic or aerobic digestion systems.

stages of approximately 8.8 and 6.1 g/l. The volume of the aerobic stage is approximately 32 percent of the volume of the anaerobic/anoxic stages.

- The membrane tank of the BNR-MBR system is designed with the same characteristics as the new flowsheet membrane/bioreactor tank but at the sidewater depth equal to that necessary to accommodate submergence of the GE hollow-fiber membranes (i.e., 2.7 m). The operating membrane area is equivalent to that assumed required for the new flowsheet membrane/ bioreactor but the membrane on-off airflow cycle in this case is 10/30 (i.e., 10 seconds on, 30 seconds off).
- A chemical feed system is provided to store and meter methanol to the post-anoxic stage. The system is designed to provide the addition of 63 l/h of a 100 percent methanol solution. A back-up ferric chloride based chemical feed system is included to ensure the effluent total P requirement of 0.1 mg/l can be met.
- The aerobic digestion step consists of two, parallel operating rectangular aerobic digesters dimensioned to represent a total volume of approximately 2000 m^3.

The design characteristics of the new flowsheet and the conventional flowsheet were used to develop complete plant system designs including headworks, plant odor control requirements, required interstage pump stations, and equipment enclosures and/or building requirements. The information allowed the flowsheets to be compared on the basis of energy usage and capital costs, and to estimate the difference in the site plan required for the flowsheets. It is estimated the new flowsheet plant will require approximately 75 percent of the space required for the conventional plant. A major reason for this difference is the total volume of the major reactor vessels making up the new flowsheet is approximately 50 percent of the corresponding total for the conventional flowsheet. It is estimated the new flowsheet will reduce the energy required for treatment plant operation by over 99 percent according to the energy balance results presented in Table 2. The major energy need in the new flowsheet is that associated with the aerobic MBR. The energy balance implies a potential to generate energy in the treatment of municipal wastewater provided a more energy efficient MBR membrane system specific to this low SRT application can be developed. The capital cost for the new flowsheet treatment plant is estimated at approximately 92 percent of the cost of the conventional treatment plant (Table 3). An analysis of yearly operating costs for the two treatment plants excluding energy costs, implies no significant difference in this cost assuming the conventional plant can operate throughout the year with no ferric chloride addition. On this basis, the amount of excess solids from the new and the conventional flowsheet digesters is calculated at 1200 and 2200 kg/day, respectively.

Table 3 | New flowsheet and conventional flowsheet capital costs[a]

Item	Cost, $ × 1000 New Flowsheet	Conventional Flowsheet
Headworks and Plant Wide Odor Control[b]	4100	4100
Aerobic or BNR MBR System[c]	6600	13,900
Reactive Filtration System[d, e]	2050	–
Membrane Thickener System[f]	1700	–
Aerobic or Anaerobic Digestion System[e, g]	2593	2300
Centrifuge Solids Dewatering System[e, h]	3400	4400
ZAR System[e, i]	2200	–
Subtotal	22,643	24,700
Site Work@ 20%	4529	4940
Electrical @ 14%	3170	3458
Instrumentation & Control @ 10%	2264	2470
Total	32,606	35,568
Contingency @ 20%	6521	7114
Total With Contingency	39,127	42,682

[a] Cost values15%.

[b] Assumed equivalent for both flowsheets. Headworks includes influent pumping, coarse screening, grit removal, fine screening and screenings washing. Appropriate building included.

[c] Includes all required equipment, tankage, tank covers, and appropriate building. Membrane tank for both flowsheets consists of 5, equally sized trains with 4 in operation. Conventional flowsheet includes methanol feed system and back-up ferric chloride chemical feed system for P removal.

[d] P removal CBFs composed of 7 filters in a single tank. Includes ferric chloride chemical feed system.

[e] Building allotment or appropriate enclosure included for certain equipment or complete system.

[f] Membrane thickener tank consists of 3, equally sized trains with 2 in operation.

[g] Includes pretreatment system, and biogas handling, conditioning and utilization equipment (i.e., microturbine) for the new flowsheet. Anaerobic MBR membrane system consists of three, skidded assemblies with two in operation.

[h] Dewatering of reactive filtration backwash solids from solid-liquid separator not included.

[i] ZAR system tank consists of 3, equally sized trains with 2 in operation while other undergoing media regeneration or in standby.

TECHNICAL AND ECONOMIC HURDLES

Despite the implied advantages of the new flowsheet relative to current conventional methods for achieving complete treatment of wastewater, there are a number of technical and economic hurdles which must be overcome in order for the new flowsheet to be viewed as an attractive alternative, as discussed elsewhere (Sutton *et al.* 2009b). Important hurdles include the likely need for development of a more efficient membrane system for the low SRT aerobic MBR application, the need to verify model assumptions associated with the aerobic MBR and anaerobic digestion systems, and the need for field demonstration of the new flowsheet concept.

SUMMARY

A municipal wastewater treatment flowsheet has been developed which achieves the goal of energy sustainability and water and nutrient recovery, while minimizing residual solids production and the release of GHGs. Although computer modeling supports the major claimed advantages of the new flowsheet and a quantitative evaluation implies an economic advantage relative to a current conventional method, there are various technical and economic hurdles to overcome in order for the new flowsheet to be viewed as an attractive alternative to conventional methods for achieving near complete treatment of wastewater.

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