SIDESTREAM TREATMENT COMPARISON OF POST AEROBIC DIGESTION AND ANAMMOX

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Abstract

This manuscript presents a comparison of Post Aerobic Digestion (PAD) and Anaerobic Ammonium Oxidation (Anammox) as sidestream treatment technologies.

Both technologies are excellent options for the reduction of nitrogen recycled back to the liquid stream without the need for supplemental carbon or alkalinity. However, the achievement of this goal is where the similarities between the two technologies end. PAD is a recently developed advanced digestion process where aerobic digestion is designed to follow anaerobic digestion. The most significant driver for selecting PAD is the reduction of nitrogen recycled back (>95% removal) to the liquid stream without the need for supplemental carbon or alkalinity (Bauer, *et al*., 2015, Johnson *et al.,* 2013 and Menniti *et al.* 2010). Other significant benefits include volatile solids reduction (Bauer *et al.,* 2014 and Parravicini *et al.,* 2006), odor reduction (Kumar *et al.*, 2006), and struvite formation reduction. Anammox harnesses a specific species of autotrophic bacteria that, in conjunction with ammonia oxidizing bacteria can achieve partial nitritation/deammonification (or, the conversion of nitrite to nitrogen gas). Similar to PAD, the most significant driver for selecting Anammox is the reduction of nitrogen recycled back (90% removal) to the liquid stream without the need for supplemental carbon or alkalinity (Nifong *et al.,* 2013 and Daigger *et al.,* 2011). In addition, the Anammox process if very energy efficient requiring about 60% less oxygen than conventional nitrification and denitrification.

The manuscript describes the unique benefits and challenges of each technology. Example installations are presented with a narrative of how and why the technology was selected. A whole plant simulator is used to compare and contrast the mass balances and net present value costs for each technology on an “apples to apples” basis. The discussion includes descriptions of conditions under which each technology would potentially be the most beneficial and cost-effective against a baseline, non-sidestream treatment equipped facility, including how best to integrate these facilities with other technologies such as thermal hydrolysis and phosphorous recovery.

Keywords

Post Aerobic Digestion, Anammox, advanced digestion, enhanced digestion, nutrient removal, sidestream, thermal hydrolysis, phosphorus recovery.

Introduction

Post Aerobic Digestion (PAD) and Anaerobic Ammonium Oxidation (Anammox) are both sidestream treatment technologies which are excellent options for the reduction of nitrogen recycled back to the liquid stream without the need for supplemental carbon or alkalinity. However, the achievement of this goal is where the similarities between the two technologies end. This paper includes a discussion of the unique benefits and challenges of each technology, including a presentation of example full-scale installations, and an “apples to apples” comparison of the mass balances and net present value costs for each technology using a whole plant simulator. The conclusions to this paper will be descriptions of conditions under which each technology would potentially be the most beneficial and cost-effective.

Post Aerobic Digestion

PAD is a recently developed advanced digestion process where aerobic digestion is designed to follow anaerobic digestion. The most significant driver for selecting PAD is the reduction of nitrogen recycled back to the liquid stream without the need for supplemental carbon or alkalinity (Johnson *et al.,* 2013 and Menniti *et al.* 2010). Average total inorganic nitrogen (TIN) removal of 95.0 percent and average PAD effluent TIN of 26 milligrams per liter (mg/L) is demonstrated for an existing full-scale PAD facility in Figure 1. Other significant benefits include volatile solids reduction (Bauer *et al.,* 2014 and Parravicini *et al.,* 2006), odor reduction (Kumar *et al.*, 2006), and struvite stabilization. Challenges to PAD, which have been overcome by operational controls and engineered solutions, include significant biological heat generated by the process and foam.

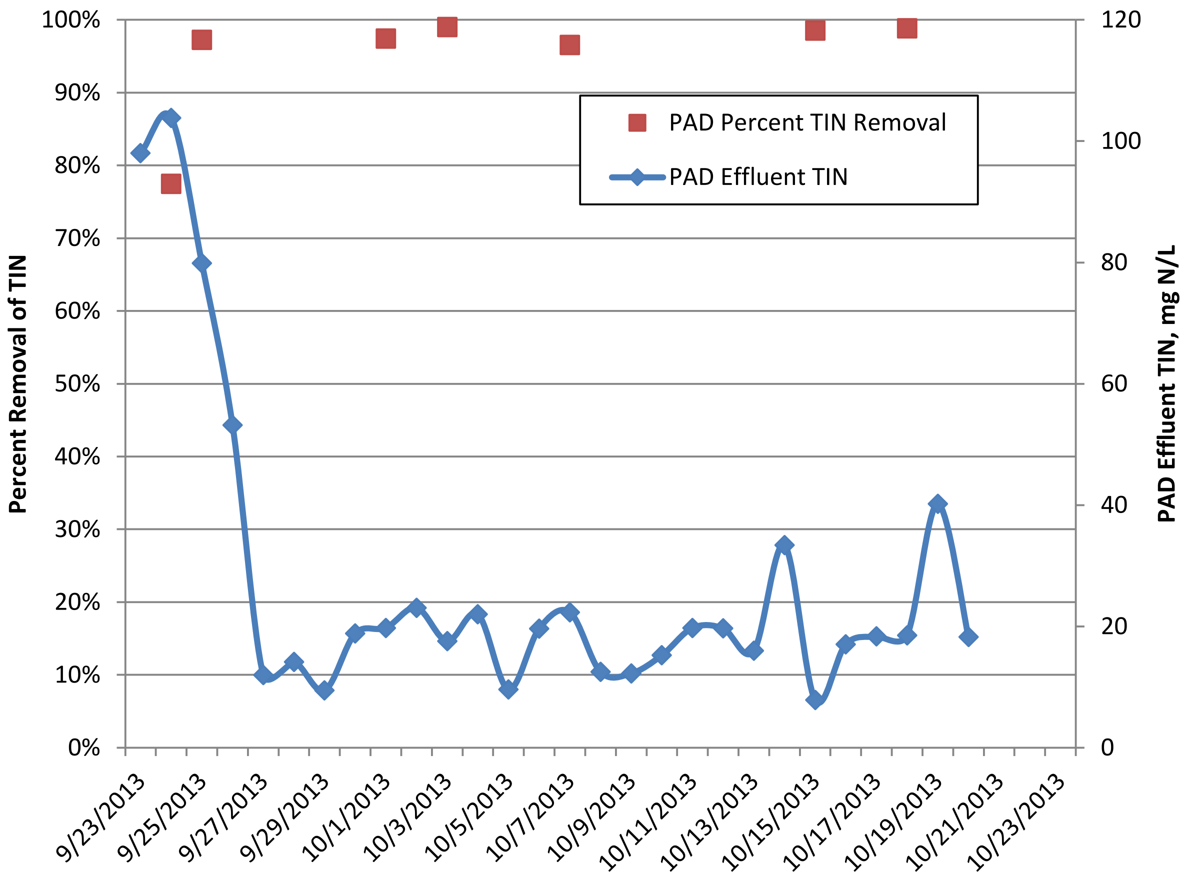


Figure 1. SCRWRF Post Aerobic Digestion Performance During the Acceptance Test Period

An example of an existing full-scale PAD facilities is at the Spokane County Regional Water Reclamation Facility (SCRWRF) which was placed into service in late 2011 (see Figure 2). PAD was implemented at the SCRWRF in order to help achieve strict nutrient removal criteria including a maximum month effluent limitation of 10 mg/L total nitrogen (TN) and a maximum seasonal (April through October) average of 0.05 mg/L total phosphorus (TP). Additionally, the Spokane County staff desired a post digestion solids storage tank that could provide at least 8-10 days of storage, and this storage tank presented an opportunity for an ideal location for PAD by simply converting an anaerobic storage tank to an aerobic one.

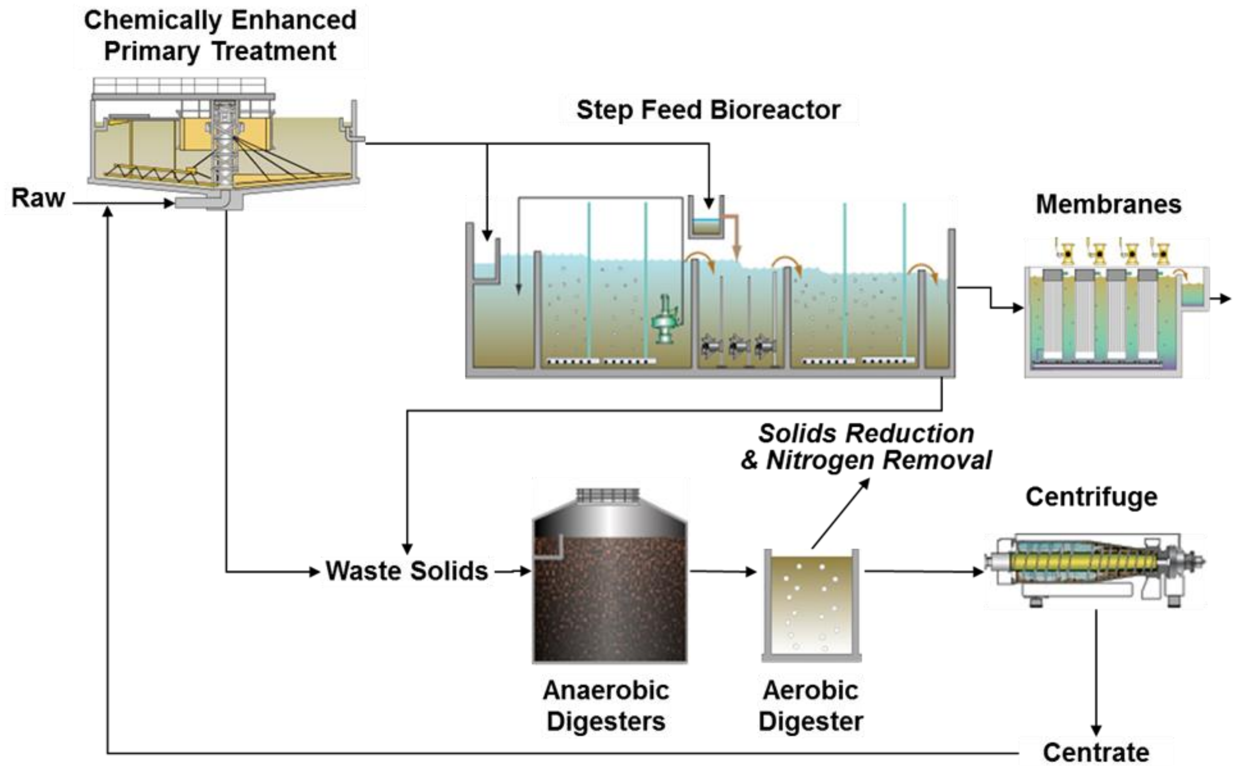


Figure 2. SCRWRF Process Flow Diagram With Post Aerobic Digestion

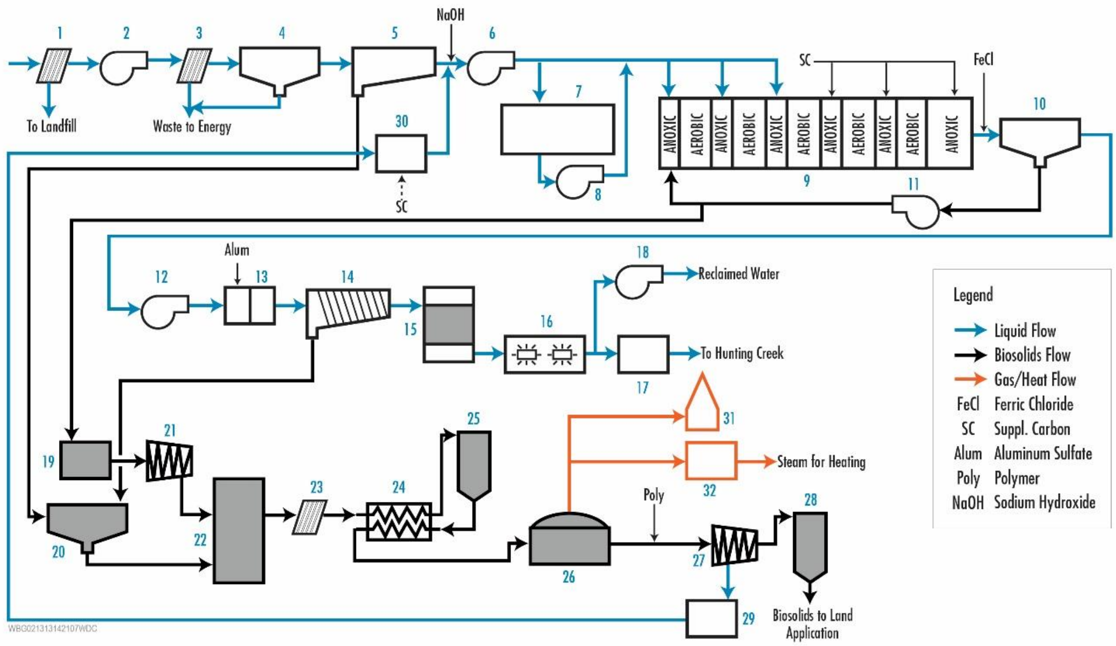
An example of a full-scale PAD facility currently under construction is at the Denver Metro Wastewater Reclamation District's (MWRD's) Northern Treatment Plant (NTP) which will be placed into service in 2016. The MWRD selected PAD for implementation at the NTP as a cost-effective way to help achieve strict nutrient removal criteria including a 30-day average effluent limitation of 3 mg/L TN and annual average of 0.1 mg/L TP while also reducing biosolids hauling costs. The MWRD typically hauls biosolids 50-100 kilometers (km, 31-62 miles) to both private and District-owned land application sites.

Anammox

Anammox harnesses a specific species of autotrophic bacteria that can achieve partial nitritation-deammonification (or, the conversion of ammonia and nitrite to nitrogen gas) under anoxic conditions. Anammox bacteria works alongside ammonia oxidizing bacteria under partial aerobic\partial anoxic conditions to ultimately convert ammonia to nitrogen gas without fully nitrifying and denitrifying.

Similar to PAD, the most significant driver for selecting Anammox is the reduction of nitrogen recycled back to the liquid stream without the need for supplemental carbon or alkalinity (Nifong *et al.,* 2013 and Daigger *et al.,* 2011). Typical ammonia removal for operational Anammox systems range between 75 and 90 percent. Another significant benefit includes lower energy consumption requiring a fraction of the oxygen demand as compared to conventional nitrification (WERF, 2009). Challenges to Anammox which have been overcome by operational controls and engineered solutions include the slow growth of the Anammox bacteria as well as competition with nitrite oxidizing bacteria.

One example of a facility that is currently in the process of implementing a full-scale sidestream Anammox system is the Alexandria Renew Enterprises (AlexRenew) Water Resources Recovery Facility (WRRF) (see Figure 3). AlexRenew considered Anammox as part of their facility upgrades in response to a Virginia state regulatory requirement to remove 62 percent of 2005 levels of effluent nitrogen by 2011. AlexRenew ultimately selected Anammox because it could achieve significant nitrogen removal with reduced supplemental chemical addition and significantly less electrical usage for aeration.



Unit Processes

1	Coarse Screens	9	Biological Reactor Basins	17	Post-Aeration Channels	25	Pasteurization Tanks
2	Raw Sewage Pumps	10	Secondary Settling Tanks	18	Reclaimed Water Pumps	26	Anaerobic Digesters
3	Fine Screens	11	Return Activated Sludge Pumps	19	Raw Sludge Blending Tanks	27	Dewatering Centrifuges
4	Vortex Grit Chambers	12	Intermediate Pumps	20	Gravity Thickeners	28	Biosolids Silos
5	Primary Settling Tanks	13	Rapid Mix/Floc.Tanks	21	Thickening Centrifuges	29	Centrate Storage Tanks
6	Primary Effluent Pumps	14	Tertiary Settling Tanks	22	Thickened Sludge Eq. Tanks	30	Centrate Pre-Treat. Reactors
7	Nutrient Mgmt. Facility	15	Gravity Filters	23	Sludge Screenings Presses	31	Gas Flares
8	Nutrient Mgmt. Pumps	16	UV Disinfection	24	Heat Exchangers	32	Biogas Boilers

Figure 3. AlexRenew WRRF Process Flow Diagram With Sidestream Anammox

Methodology

A simulator based comparison is appropriate for comparing these two technologies because none of the existing facilities are directly comparable to each other. CH2M's proprietary ASM-based Professional Process Design and Dynamics (Pro2D^2) whole plant simulator was used as the comparison tool. The following Pro2D^2 models representing three hypothetical water reclamation facilities were developed:

- The baseline facility (Figure 4) which contains no sidestream treatment,
- A facility that treats anaerobic digester effluent with PAD (Sidestream Treatment with PAD, Figure 5), and
- A facility that treats the liquid removed by dewatering with Anammox bacteria (Sidestream Treatment with Anammox, Figure 6).

By definition, a sidestream is any flow stream resulting from the dewatering or treatment of biosolids that is returned to the liquid treatment train. Sidestream flow streams are targeted for nutrient removal because they exhibit relatively small flow with concentrated nutrient loading back to the liquid treatment train. However, as shown in the process flow diagrams for the three models illustrated in Figures 4, 5, and

6, respectively, the PAD and Anammox technologies target different sidestream flow streams; PAD targets digester effluent while Anammox targets the filtrate or centrate produced from dewatering.

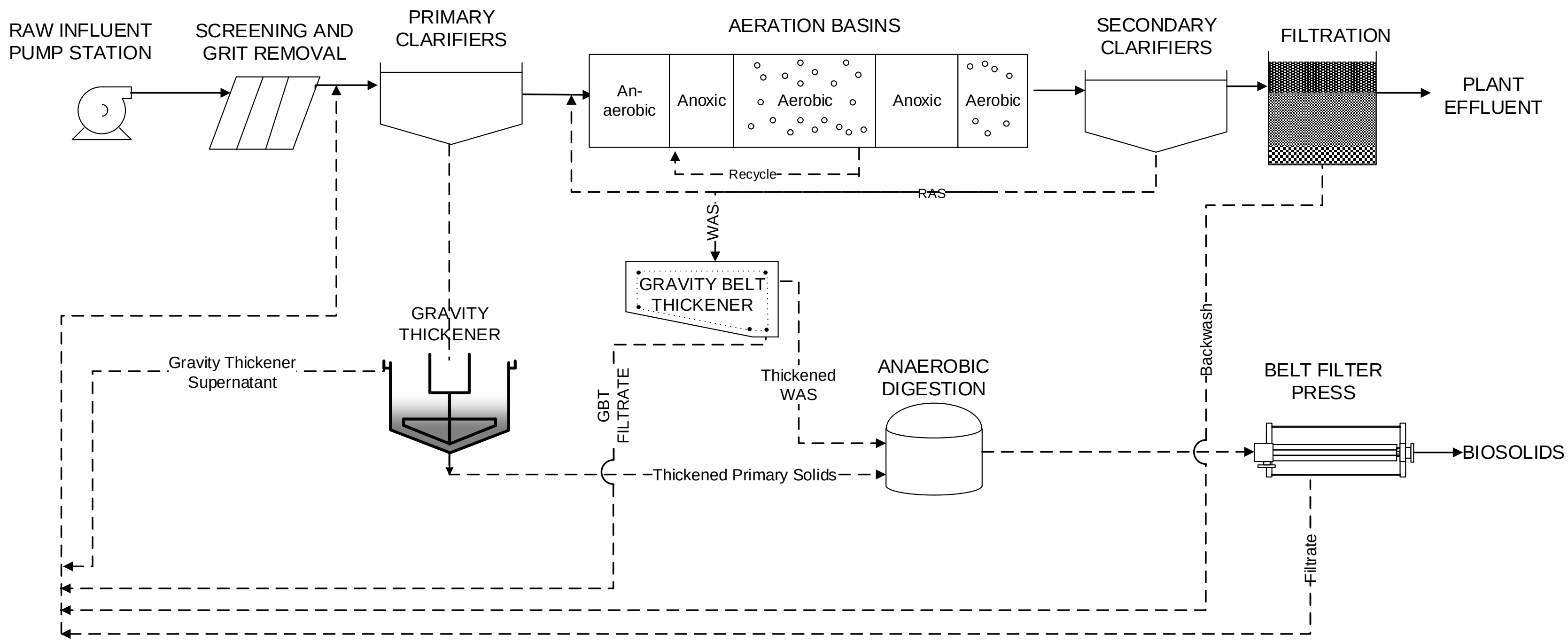


Figure 4. Process Flow Diagram for the Baseline Water Reclamation Facility (No Sidestream Treatment)

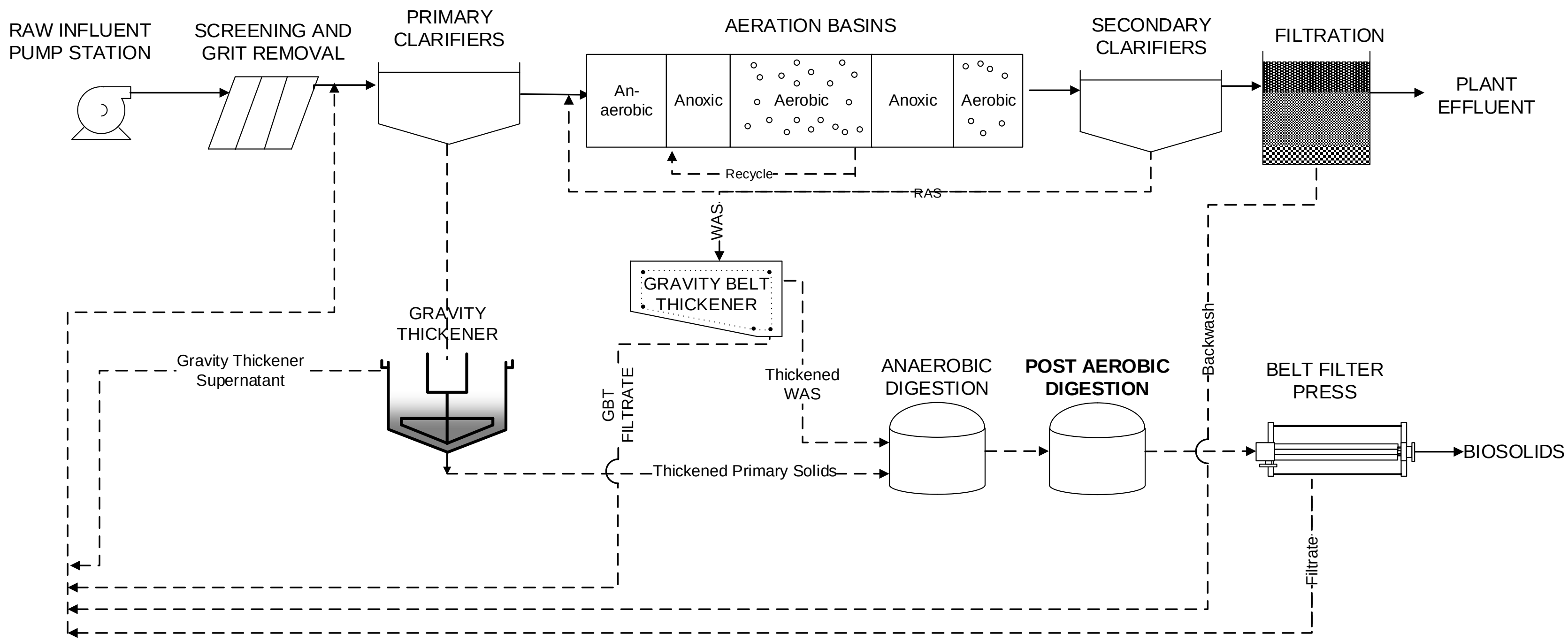


Figure 5. Process Flow Diagram for Sidestream Treatment with PAD

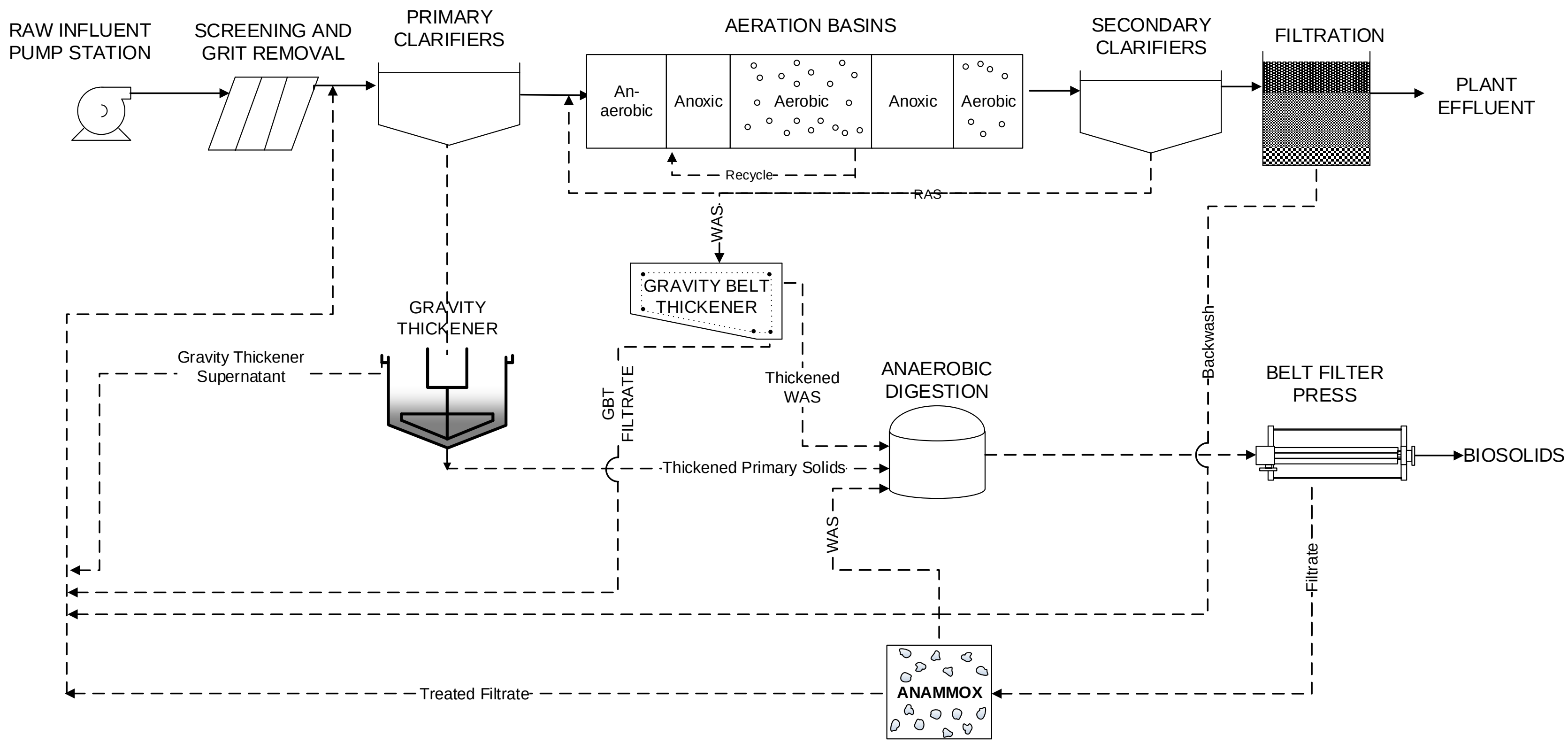


Figure 6. Process Flow Diagram for Sidestream Treatment with Anammox

The following were assumed for each of the three models:

- Raw influent wastewater flow of 75.7 million liters (ML) per day [20 million gallons (MG) per day]
- Raw influent wastewater characteristics as shown in Table 1
- 30-day average effluent limitations of 10 mg/L total suspended solids (TSS), 10 mg/L biochemical oxygen demand (BOD), 1 mg/L NH3, 5.0 mg/L TN, and 1.0 mg/L TP. Operational effluent limits were 4.5 mg/L TN and 0.8 mg/L TP
- Modified Bardenpho (5-stage) configuration of the aeration basins, selected in order to achieve the required nutrient removal requirements
- Aeration basin solids retention time of 8.5 days
- Sludge Volume Index of 120 mL/g
- Nitrification safety factor of 2.5
- Solids handling facilities in operation 24 hours per day and 7 days per week
- Beneficial use of biosolids via land application

Table 1. Raw Influent Wastewater Characteristics Assumed for All Models

Parameter	Value	Unit
BOD	250	mg/L
TSS	240	mg/L
Volatile Suspended Solids (VSS)	192[a]	mg/L
Total Kjeldahl Nitrogen (TKN)	39	mg/L as N
Ammonia-Nitrogen (NH3)	30	mg/L as N
TP	6	mg/L
Alkalinity	250	mg/L
Temperature	20	°C

[a] Assumes VSS is 80 percent of TSS

Capital and life cycle costs to compare the results of the three models were developed using CH2M's Parametric Cost Estimating System (CPES). CPES is a proprietary conceptual cost estimating tool with algorithms built into each unit process module which allows the costs to be adjusted based on project-specific information supplied by the user.

Design criteria assumed in the development of the costs are listed as follows for each of the unit processes (each unit process is assumed to be constructed at grade unless otherwise specified):

- A raw influent pump station assuming five duty submersible pumps designed for 22.9 meters (m) [75 feet (ft)] total dynamic head (TDH), and a 6.7 m (22 ft) depth of burial.
- Screening facilities assuming three duty mechanical screens designed for a screen opening of 6.4 millimeters (0.25 inches), and a channel width of 1.12 m (3.67 ft).
- Grit removal and classifier facilities assuming two grit chambers and two duty grit pumps designed for a channel width of 1.12 m (3.67 ft).
- Primary clarifiers assuming three, circular clarifiers each designed with a 29 m (95 ft) diameter and 4.88 m (16.0 ft) side water depth (SWD).
- A primary solids pump station assuming three duty pumps designed for 22.9 m (75 ft) TDH and a 6.1 m (20.0 ft) depth of burial.
- Aeration basins assuming the following:
    - Four trains, each containing 8.9 ML (2.35 MG).
    - Uncovered basins

- 6.1 m (20.0 ft) SWD
- 3.05 m (10.0 ft) depth of burial
- Two total axial-flow nitrified recycle pumps designed for a nitrified recycle rate of four times the influent flow (or, 4Q), each with a variable speed drive (VSD) and a capacity of 27.9 cubic meters per minute (m^3/min) [7,360 gallons per minute (gpm)] and 1.52 m (5.0 ft) TDH
- Six total mixers designed for a target mixing intensity of 0.00986 kW/m^3 (50 hp/MG)
- Four duty, multi-stage aeration blowers located in a separate building and designed for a blower efficiency of 70 percent.

- Secondary clarifiers assuming four, circular clarifiers each designed with a 33.5 m (110 ft) diameter and 4.88 m (16.0 ft) SWD.
- A return activated sludge (RAS) and waste activated sludge (WAS) pump station assuming four duty RAS pumps and two duty WAS pumps each designed with a VSD and designed for 9.1 m (30 ft) TDH and a 3.05 m (10.0 ft) depth of burial.
- Ten deep bed granular media filters designed for an average hydraulic loading rate of 81.48 liters per day per square meter (L/d·m^2) [2.0 gallons per day per square foot (gpd/ft^2)] and a maximum hydraulic loading rate of 161.7 L/d·m^2 (3.97 gpd/ft^2).
- Thickening of primary solids with two gravity thickeners each designed for a 12.2 m (40 ft) diameter, 90 percent solids capture, and a thickened solids concentration of 5% TS.
- Thickening of secondary solids with two gravity belt thickeners (GBT) each designed for 92 percent solids capture, 2 meter belt size, and a thickened solids concentration of 5% TS.
- Mesophilic anaerobic digestion assuming three digesters each designed with 8.53 m (28 ft) SWD, 23.8 m (78 ft) diameter, hydraulic mixing, two hours of biogas storage, and usage of 60 percent of the biogas in boilers (flaring 40 percent).
- Dewatering with two belt filter presses (BFP) each designed for 92 percent solids capture, 2 meter belt size, 320.3 kilograms per hour per meter (706 pounds per hour per meter), 0.284 m^3/min per meter (75 gpm per meter), and a dewatered biosolids cake concentration of 24% TS.

The Baseline (No Sidestream Treatment) model determined that 778 kilograms per day (1,715 pounds per day) of carbon is necessary to achieve the effluent TN limitations. Thus, this model assumes a methanol storage and feed facility designed for one 3.66 m (12 ft) diameter tank to be able to store a minimum of 30 days of maximum month chemical and four dosage pumps. The carbon storage and feed facility is assumed to be enclosed within a separate building.

The PAD model determined that aerobic digester volume of 4,656 m^3 (1.23 MG) is optimal for employing PAD at this hypothetical water reclamation facility. Thus, this model assumes two rectangular PAD tanks each designed with 19.8 m (65 ft) length, 20.4 m (67 ft) width, 5.8 m (19 ft) SWD, two duty blowers, and medium bubble diffusers. This model demonstrated that the effluent limitations could be achieved without any supplemental alkalinity or carbon.

The Anammox model was based around the DEMON® process with an estimated total reactor volume of 1,079 m^3 (0.285 MG) for this hypothetical water reclamation facility. This volume is assumed to be configured into two square sequencing batch reactor (SBR) basins with an additional equal sized basin for equalization as the DEMON® process does not feed the reactor continuously. Each basin is designed with a 4.9 m (16 ft) SWD, 10.52 m (34.5 ft) length and width, cyclone wasting with cyclone feed pump, basin mixer, decanter, diffused aeration, and a 0.61 m (2.0 ft) depth of burial. The two SBRs are fed from the equalization tank with dedicated submersible feed pumps. Aeration is provided to each reactor by two duty blowers. This model also demonstrated that the effluent limitations could be achieved without any supplemental alkalinity or carbon.

Additional capital, annual, and life cycle assumptions used for the cost evaluation of the three models is displayed in Table 2.

Table 2. Capital, Annual, and Life Cycle Cost Assumptions

Item	Value	Units
Life Cycle Assumptions:		
Life of Study	20	years
Discount Rate	5.0	%
Inflation Rate	3.0	%
Capital Cost Assumptions:		
Start of Construction	2015	
Construction Duration	2	years
Markup Factor[a]	2.38	unitless
Annual Cost Assumptions[b]:		
Electricity Cost	0.0768	$/kWh
Maintenance and Repair Cost	3.0	%/year of equipment cost
Biosolids Hauling Cost	$20.58[c]	$/wet metric ton
	$18.67[c]	$/wet U.S. ton
Biosolids Disposal Cost	$33.07[d]	$/wet metric ton
	$30.00[d]	$/wet U.S. ton
Trash Hauling and Disposal Cost[e]	$78.33	$/cubic meter
	$59.89	$/cubic yard
Revenue	$0	$/year
Contingency[f]	20	% of annual costs

[a] The markup factor includes contractor indirect costs (overhead, profit, mobilization, demobilization, bonds, and insurance), contingency, and non-construction costs (permitting, engineering, services during construction, commissioning, and startup).
[b] Labor is not included in annual cost calculations.
[c] Assumes a round trip haul distance of 80.5 km (50 miles).
[d] Assumes land application of digested biosolids.
[e] For the hauling and disposal of screenings and grit. Assumes a round trip haul distance of 40.3 km (25 miles).
[f] Includes vehicles, laboratory tests, office equipment, and other miscellaneous items.

Results

Differences between the baseline, the sidestream treatment with PAD, and the sidestream treatment with Anammox models are presented in this section in terms of mass balances to illustrate nutrient removals and life cycle costs.

Mass Balances

The mass balances surrounding sidestream treatment generated from the simulations for the baseline, the sidestream treatment with PAD, and the sidestream treatment with Anammox models are summarized in Table 3. Because PAD and Anammox target different sidestream flow streams, the appropriate flow stream in the baseline model is used for comparison.

Table 3. Sidestream Simulation Results

Parameter	PAD Baseline (No Sidestream Treatment)[a]	Sidestream Treatment with PAD	Anammox Baseline (No Sidestream Treatment)[b]	Sidestream Treatment with Anammox
Sidestream Prior to Treatment:				
Flow, m3/d	460	460	880	870
BOD, mg/L (kg/d)	3,600 (1,700)	3,500 (1,600)	200 (180)	200 (170)
TSS, mg/L (kg/d)	28,000 (13,000)	28,000 (13,000)	1,200 (1,000)	1,200 (1,000)
Volatile Suspended Solids (VSS), mg/L (kg/d)	17,000 (8,000)	17,000 (7,900)	720 (640)	720 (630)
NH3, mg-N/L (kg-N/d)	940 (430)	860 (400)	440 (390)	420 (370)
TKN, mg-N/L (kg-N/d)	1,800 (850)	1,800 (820)	490 (430)	470 (410)
Nitrate (NO3), mg-N/L (kg-N/d)	0 (0)	0 (0)	0 (0)	0 (0)
TIN, mg-N/L (kg-N/d)	940 (430)	860 (400)	440 (390)	420 (370)
TN, mg-N/L (kg-N/d)	1,800 (850)	1,800 (820)	490 (430)	470 (410)
TP, mg/L (kg/d)	1,900 (900)	2,100 (970)	543 (480)	548 (477)
Sidestream After Treatment:				
Flow, m3/d	460	460	880	870
BOD, mg/L (kg/d)	3,600 (1,700)	670 (310)	200 (180)	27 (24)
TSS, mg/L (kg/d)	28,000 (13,000)	25,000 (11,000)	1,200 (1,000)	96 (83)
VSS, mg/L (kg/d)	17,000 (8,000)	14,000 (6,400)	720 (640)	58 (50)
NH3, mg-N/L (kg-N/d)	940 (430)	10 (4.4)	440 (390)	43 (37)
TKN, mg-N/L (kg-N/d)	1,800 (850)	720 (330)	490 (430)	59 (51)
NO3, mg-N/L (kg-N/d)	0 (0)	45 (20)	0 (0)	50 (43)
TIN, mg-N/L (kg-N/d)	940 (430)	54 (25)	440 (390)	93 (80)
TN, mg-N/L (kg-N/d)	1,800 (850)	760 (850)	490 (430)	110 (94)
TP, mg/L (kg/d)	1,900 (900)	2,100 (970)	540 (480)	520 (450)

[a] PAD baseline for sidestream treatment is the anaerobic digester effluent flow stream.
[b] Anammox baseline for sidestream treatment is the BFP filtrate flow stream.

As shown in Table 3, the mass balance values for sidestream prior to treatment are similar (no more than 8 percent different) for each treatment technology compared to its respective baseline flow stream. The sidestream flow stream targeted by PAD is about half the flow and significantly higher loads compared to the sidestream flow stream treated by Anammox. Since the sidestream flow stream targeted by Anammox has had the solids removed from it via dewatering, there are significantly few solids in this flow stream.

Because PAD and Anammox target different sidestream flow streams, one way to compare the performance of the two technologies is by considering mass removal through sidestream treatment. The mass removed (sidestream prior to treatment minus sidestream after treatment) are displayed in Figure 7. Compared to Anammox, PAD achieves greater BOD, TSS, and VSS destruction, which is expected due to the VSS destruction associated with PAD. PAD also achieves greater NH3, TKN, and TN removal, which is also attributed to the VSS destruction. Anammox achieves 30 kg/d of TP removal, which is associated with the Anammox waste stream, which PAD does not have. Because there is no sidestream treatment for the baseline model, all values are zero for the baseline in Figure 7.

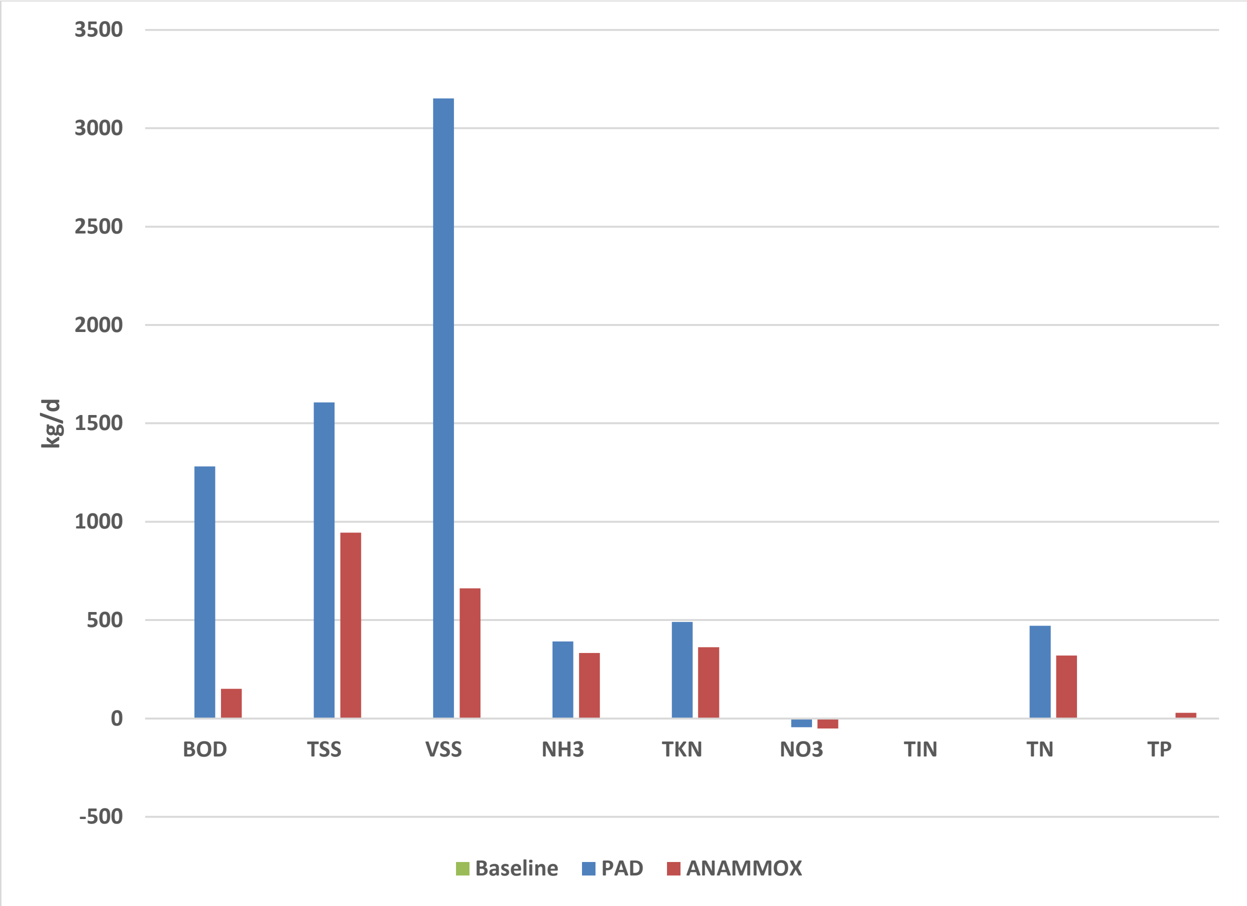


Figure 7. Sidestream Mass Loading Removal Comparison

Another way to compare the performance of the two technologies, since PAD and Anammox target different sidestream flow streams, is by comparing the quality of the liquor being returned to the head of the plant (see Table 4).

Table 4. Recycle Stream Simulation Results

Parameter	Baseline (No Sidestream Treatment)	Sidestream Treatment with PAD	Sidestream Treatment with Anammox
Filtrate Prior to Being Recycled Back to Headworks[a]:			
Flow, m3/d	880	890	860
NH3, mg-N/L (kg-N/d)	440 (390)	4.5 (4.0)	43 (37)
TKN, mg-N/L (kg-N/d)	490 (430)	45 (40)	59 (51)
NO3, mg-N/L (kg-N/d)	0 (0)	21 (19)	50 (43)
TIN, mg-N/L (kg-N/d)	440 (390)	25 (23)	93 (80)
TN, mg-N/L (kg-N/d)	490 (430)	66 (59)	110 (94)
TP, mg/L (kg/d)	540 (480)	620 (550)	520 (450)
Percent Change from Baseline:			
NH3, %	N/A	99%	90%
TKN, %	N/A	91%	88%
TIN, %	N/A	94%	79%
TN, %	N/A	86%	78%
TP, %	N/A	-14%	5.5%

[a] Represents the recycle stream back to the headworks excluding filter backwash, GBT filtrate, and gravity thickener supernatant.

As shown in Table 4, both sidestream treatment technologies remove significant amounts of constituents from the filtrate compared to the baseline. Only nutrients are displayed in Table 4 because the solids parameters are not “apples to apples” since PAD treatment occurs prior to dewatering and Anammox treatment occurs after dewatering. PAD achieves greater NH3, TKN, and TN removal, which is attributed to the VSS destruction associated with PAD.

Simulation results for the plant effluent are summarized in Table 5.

Table 5. Plant Effluent Simulation Results

Parameter	Baseline (No Sidestream Treatment)[a]	Sidestream Treatment with PAD	Sidestream Treatment with Anammox
Plant Effluent:			
Flow, m3/d (mgd)	76,000	76,000	76,000
BOD, mg/L (kg/d)	1.7 (130)	1.7 (130)	1.7 (130)
TSS, mg/L (kg/d)	3.1 (240)	3.1 (240)	3.1 (240)
VSS, mg/L (kg/d)	2.1 (160)	2.0 (150)	2.0 (160)
NH3, mg-N/L (kg-N/d)	0.4 (30)	0.4 (31)	0.3 (19)
TKN, mg-N/L (kg-N/d)	1.8 (140)	1.8 (140)	1.7 (130)
NO3, mg-N/L (kg-N/d)	2.6 (200)	2.1 (160)	2.2 (170)
TIN, mg-N/L (kg-N/d)	3.0 (230)	2.5 (190)	2.5 (190)
TN, mg-N/L (kg-N/d)	4.5 (340)	3.9 (300)	3.9 (300)
TP, mg/L (kg/d)	0.44 (33.5)	0.49 (37.1)	0.45 (34.5)

[a] A carbon dose of 778 kg/d is assumed in order to achieve the effluent values listed.

The effluent concentrations listed in Table 5 confirm that the effluent limitation goals described in the Methodology section for BOD, TSS, TN, and TP were accomplished by all three models. The baseline model could not achieve the effluent limitations without the addition of supplemental carbon.

The effluent simulation results in Table 5 do not indicate any significant differences between the two sidestream treatment technologies compared to each other or to the baseline. Energy use was evaluated with the annual costs to determine if either or both of the sidestream treatment technologies are able to accomplish this plant effluent quality with less energy than the baseline.

Simulation results for the biosolids are summarized in Table 6.

Table 6. Biosolids Simulation Results

Parameter	Baseline (No Sidestream Treatment)	Sidestream Treatment with PAD	Sidestream Treatment with Anammox
Biosolids:			
TSS, kg/d	12,000	10,000	12,000
VSS, kg/dV	7,400	5,900	7,200
NH3, kg-N/d	47	0.4	46
TKN, kg-N/d	422	290	418
TN, kg-N/d	422	292	418
TP, kg/d	420	418	423
Percent Change from Baseline:			
TSS, %	N/A	13%	1.3%
VSS, %		20%	2.1%
NH3, %	N/A	99%	2.1%
TKN, %	N/A	31%	0.8%
TN, %	N/A	31%	0.8%
TP, %	N/A	0.5%	-0.6%
Mass Change from Baseline:			
TSS, kg/d	N/A	1,500	160
VSS, kg/d	N/A	1,500	150
NH3, kg-N/d	N/A	46	1.0
TKN, kg-N/d	N/A	130	3.5
TN, kg-N/d	N/A	130	3.5
TP, kg/d	N/A	2.0	-2.4

As shown in Table 6, and as illustrated in Figure 8, PAD demonstrates significantly less TSS, VSS, NH3, TKN, and TN in the biosolids that have been treated with PAD compared to the baseline and compared to Sidestream Treatment with Anammox. Although this represents a reduction in biosolids quantity to be hauled with PAD (which is manifested in the annual cost comparison), these results could have implications, potentially positive or negative, for nutrient loading for land application.

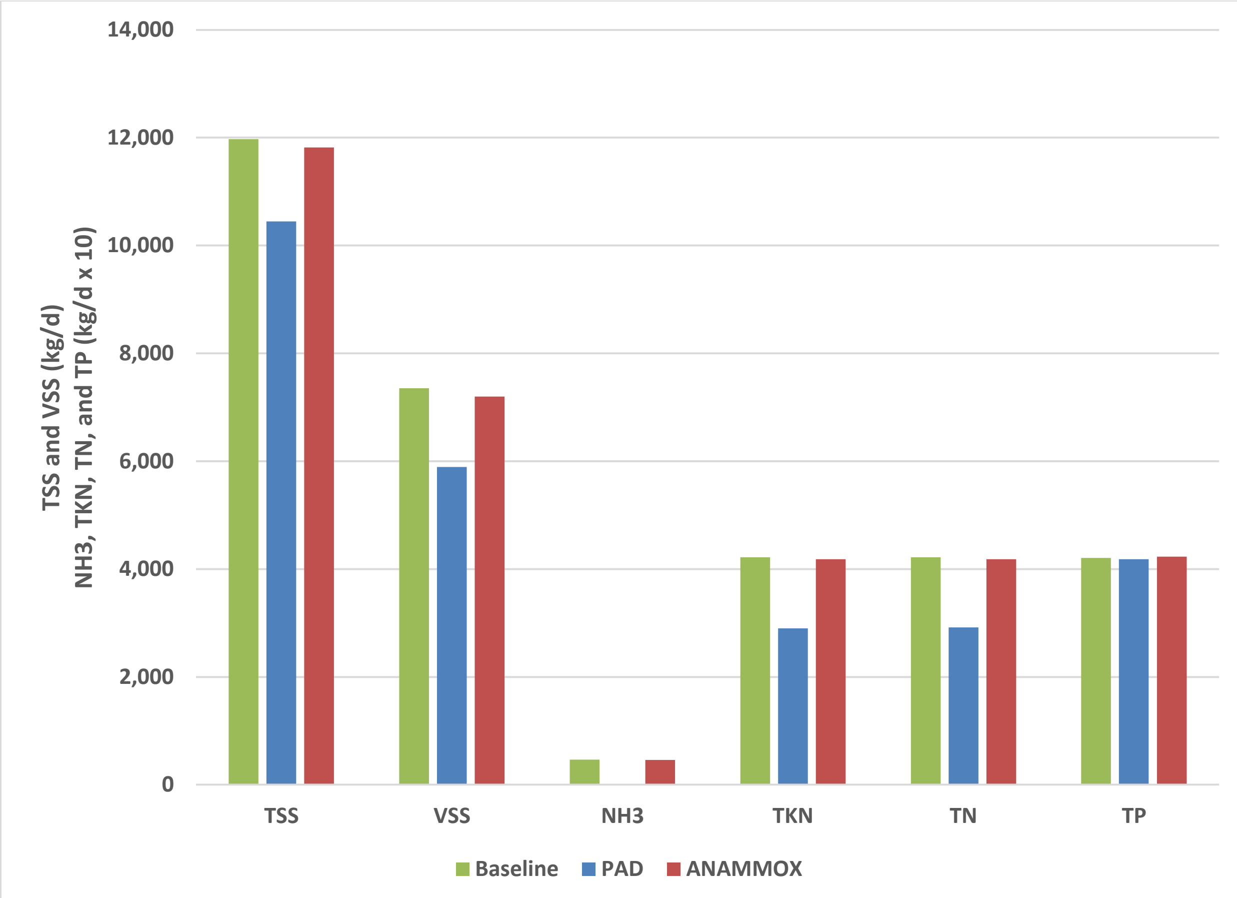


Figure 8. Biosolids Characterization Comparison

Further Evaluation of Energy Use, Chemical Use, and Biosolids Production

Because energy use, chemical use, and biosolids production are the most prominent annual costs for comparing PAD and Anammox, these three annual costs are explored in further depth in this section. The differences in energy use, chemical use, and biosolids production for the sidestream technologies, and the resulting annual costs, are summarized in Table 7.

Table 7. Comparing Energy Use, Chemical Use, and Biosolids Production for Sidestream Treatment Technologies[a]

	Baseline (No Sidestream Treatment)	Sidestream Treatment with PAD	Sidestream Treatment with Anammox
Energy Use			
Sidestream Treatment, kW	-	24	23
Methanol Feed, kW	5	-	-
Aeration Basins, kW	594	551	553
Anaerobic Digestion, kW	129	129	129
Anaerobic Digestion Energy Generation, kW[b]	(462)	(452)	(457)
Net Energy, kW	266	252	247
Annual Energy Consumption, kWh/yr	2,330,000	2,210,000	2,160,000
Annual Energy Cost[c], $/yr	**$179,000**	**$170,000**	**$166,000**
Energy Cost Compared to Baseline, $/yr		-$9,000	-$13,000
Energy Cost Compared to Baseline, %		-5.0%	-7.3%
Chemical Use			
Methanol Consumption, kg/d (lb/d)	778 (1,715)	-	-
Methanol Consumption, MG/yr (dry tons/yr)	284 (313)	-	-
Annual Methanol Cost[d], $/yr	**$139,000**	**-**	**-**
Biosolids Production			
Biosolids Production, kg/d (lb/d)	7,982 (17,598)	6,965 (15,354)	7,878 (17,368)
Biosolids Production, dry metric tons/day	8.0	7.0	7.9
Biosolids Production, wet metric tons/day[e]	33.3	29.0	32.8
Annual Land Application Cost[f], $/yr	**$651,000**	**$568,000**	**$643,000**
Cost Compared to Baseline, $/yr		-$83,000	-$8,000
Cost Compared to Baseline, %		-12.7%	-1.2%
TOTAL			
Total Estimated Annual Cost for Energy, Methanol, and Biosolids Beneficial Use, $/yr	**$969,000**	**$738,000**	**$809,000**
Total Cost Compared to Baseline, $/yr		-$231,000	-$160,000
Total Cost Compared to Baseline, %		-23.8%	-16.5%

[a] Values represent average annual conditions
[b] Assumes 600 BTU/ft3 and 35% energy efficiency
[c] Assumes $0.0768/kWh
[d] Assumes $443.89 per dry ton for methanol
[e] Assumes 24% TS for biosolids
[f] Assumes $53.65/wet metric ton, which is the sum of the biosolids hauling and biosolids beneficial land application costs listed in Table 2

Considering the energy use data shown in Table 7, the energy invested in sidestream treatment results in less energy required for nutrient removal in the aeration basins. For Sidestream Treatment with Anammox, the energy saved in the aeration basins overcomes the energy required for sidestream treatment and results in a net energy savings of 5.0 percent compared to the Baseline (No Sidestream Treatment). For Sidestream Treatment with PAD, a similar energy savings in the aeration basins is demonstrated and a similar amount of energy is required compared to Sidestream Treatment with Anammox, resulting in a net energy savings of 7.3 percent compared to the Baseline (No Sidestream Treatment).

Considering the chemical use data shown in Table 7, the 778 kg/d (1,715 lb/d) of methanol required to meet the effluent limitations without sidestream treatment results in an average annual cost of $139,000 for the Baseline (No Sidestream Treatment).

Considering the biosolids production data shown in Table 7, Sidestream Treatment with PAD reduces significantly more biosolids than Sidestream Treatment with Anammox (12.7 percent reduction versus 1.2 percent reduction, respectively) relative to the Baseline (No Sidestream Treatment).

Considering the energy use, chemical use, and biosolids production data combined, as shown in Table 7, Sidestream Treatment with Anammox results in a net annual cost savings of approximately 16.5 percent relative to the Baseline (No Sidestream Treatment). Due to the significantly greater hauling and land application cost savings, Sidestream Treatment with PAD demonstrates a net annual cost savings of approximately 23.8 percent relative to the Baseline (No Sidestream Treatment), which is approximately 8.8 percent greater net cost savings relative to Sidestream Treatment with Anammox. The significant savings in hauling and land application costs for Sidestream Treatment with PAD more than makes up for the energy required for treatment.

Life Cycle Costs

Capital, annual, and life cycle costs are presented in this section to compare the two sidestream treatment technologies. The cost estimate is considered a “Class 4 (Study or Feasibility) Level” estimate, as defined by the Estimate Classification Systems from the Association for the Advancement of Cost Estimating International (AACEI), and the expected range of accuracy for this estimate is +50% and -30%. All cost values presented are in 2015 US dollars.

Capital costs for the baseline, sidestream treatment with PAD, and sidestream treatment with Anammox are listed in Table 8. Capital costs assume a greenfield water reclamation facility is constructed.

Table 8. Capital Cost Comparison for Sidestream Treatment Technologies[a]

	Baseline (No Sidestream treatment)	Sidestream Treatment with PAD	Sidestream Treatment with Anammox
Influent Pump Station	$5.5	$5.5	$5.5
Screening and Grit Removal	$8.2	$8.2	$8.2
Primary Clarifiers	$4.6	$4.6	$4.6
Primary Sludge Pump Station	$1.3	$1.3	$1.3
Aeration Basins	$19.4	$19.1	$19.1
Aeration Basin Blowers	$4.4	$4.2	$4.3
Secondary Clarifiers	$7.4	$7.4	$7.4
RAS/WAS Pump Station	$4.0	$4.0	$4.0
Tertiary Filters	$15.7	$15.7	$15.7
Gravity Thickener	$2.1	$2.1	$2.1
Gravity Belt Thickener	$5.1	$5.1	$5.1
Anaerobic Digesters	$23.6	$23.6	$23.6
Belt Filter Press	$4.1	$4.1	$4.1
Carbon Feed and Storage Facility	$1.5	-	-
Anammox Facility	-	-	$3.8
Post Aerobic Digestion	-	$5.3	-
Subtotal	$106.9	$110.2	$108.8
Additional Project Costs[b]	$15.6	$16.1	$15.9
Total Construction Cost	**$122.5**	**$126.3**	**$124.7**
Percent Increase from Lowest Construction Cost	**-**	**3.1%**	**1.8%**

[a] All costs are in million dollars.

[b] Includes overall sitework, plant computer system, yard electrical, and yard piping.

As shown in Table 8, the baseline alternative offers the lowest capital cost because the cost of constructing sidestream treatment facilities is more than constructing a methanol feed and storage facility. The most significant capital cost differences occur for the Carbon Feed and Storage, Anammox, and Post Aerobic Digestion facilities. The only other facilities that differ between the three alternatives are the aeration basins and associated blower facilities because the sidestream treatment technologies results in less energy required for nutrient removal in the aeration basins.

Annual costs for the baseline (no sidestream treatment), sidestream treatment with PAD, and sidestream treatment with Anammox are listed in Table 9. Labor costs are not included in this evaluation as they are assumed to be equal.

Table 9. Annual Cost Comparison for Sidestream Treatment Technologies[a]

	Baseline (No Sidestream Treatment)	Sidestream Treatment with PAD	Sidestream Treatment with Anammox
Influent Pump Station	$0.28	$0.28	$0.28
Screening and Grit Removal	$0.63	$0.63	$0.63
Primary Clarifiers	$0.06	$0.06	$0.06
Primary Sludge Pump Station	$0.01	$0.01	$0.01
Aeration Basins	$0.24	$0.23	$0.23
Aeration Basin Blowers	$0.39	$0.35	$0.36
Secondary Clarifiers	$0.10	$0.10	$0.10
RAS/WAS Pump Station	$0.08	$0.08	$0.08
Tertiary Filters	$0.16	$0.16	$0.16
Gravity Thickener	$0.03	$0.03	$0.03
Gravity Belt Thickener	$0.12	$0.12	$0.12
Anaerobic Digesters	$0.39	$0.39	$0.39
Belt Filter Press	$0.10	$0.10	$0.10
Carbon Feed and Storage Facility	$0.24	-	-
Anammox Facility	-	-	$0.05
Post Aerobic Digestion	-	$0.10	-
Subtotal	$2.83	$2.64	$2.60
Biosolids Hauling and Land App.	$1.40	$1.20	$1.40
Standard Items[b]	$0.20	$0.20	$0.20
Total Annual Cost	**$4.43**	**$4.04**	**$4.20**
Percent Increase from Lowest Annual Cost	**9.7%**	**-**	**4.0%**

[a] Annual costs presented are capital recovery factors. All costs are in million dollars.

[b] Includes 1% capital cost for annual repair and maintenance cost, 10% miscellaneous annual costs (such as vehicles, lab tests, office equipment and other miscellaneous expenses), and 10% annual cost contingency.

As shown in Table 9, the sidestream treatment with PAD offers the lowest annual cost primarily due to the significant savings in biosolids hauling and land application due to the VSS destruction associated with PAD.

Life cycle costs for the baseline (no sidestream treatment), sidestream treatment with PAD, and sidestream treatment with Anammox are shown in Table 10.

Table 10. Net Present Value Comparison for Sidestream Treatment Technologies[a]

	Baseline (No Sidestream Treatment)	Sidestream Treatment with PAD	Sidestream Treatment with Anammox
Influent Pump Station	$9.0	$9.0	$9.0
Screening and Grit Removal	$16.1	$16.1	$16.1
Primary Clarifiers	$5.4	$5.4	$5.4
Primary Sludge Pump Station	$1.4	$1.4	$1.4
Aeration Basins	$22.3	$22.1	$22.1
Aeration Basin Blowers	$9.3	$8.6	$8.7
Secondary Clarifiers	$8.5	$8.5	$8.5
RAS/WAS Pump Station	$5.1	$5.1	$5.1
Tertiary Filters	$17.6	$17.6	$17.6
Gravity Thickener	$2.4	$2.4	$2.4
Gravity Belt Thickener	$6.6	$6.6	$6.6
Anaerobic Digesters	$28.4	$28.4	$28.4
Belt Filter Press	$5.3	$5.3	$5.3
Carbon Feed and Storage Facility	$4.5	-	-
Anammox Facility	-	-	$4.5
Post Aerobic Digestion	-	$6.5	-
Subtotal	$141.9	$143.0	$141.1
Biosolids Hauling and Disposal	$17.7	$15.4	$17.4
Standard Items[b]	$18.0	$18.6	$18.4
Total Net Present Value	**$177.6**	**$177.0**	**$176.9**
Percent Increase from Lowest Net Present Value	**0.40%**	**0.06%**	**-**

[a] All costs are in million dollars.

[b] Additional project costs are defined in Table 8 and standard items are defined in Table 9.

As shown in Table 10, the lowest net present value is similar for the baseline (no sidestream treatment), sidestream treatment with PAD, and sidestream treatment with Anammox alternatives. For planning purposes, these three alternatives are considered equivalent.

Integration of PAD and Anammox with Thermal Hydrolysis

The Thermal Hydrolysis Process (THP) provides pretreatment to the digestion process for enhanced volatile solids destruction, increased digestion capacity, increased biogas production, and improved dewaterability, among other benefits. THP consists of a series of unit processes that preheat, hydrolyze, and sterilize the sludge.

Both PAD and Anammox can be integrated as sidestream treatment processes into water reclamation facilities containing THP. Models representing hypothetical water reclamation facilities similar to those previously described but with the addition of THP prior to mesophilic anaerobic digestion were developed. The differences in energy use, chemical use, and biosolids production for the sidestream technologies with THP, and the resulting annual costs, are summarized in Table 11.

Table 11. Comparing Energy Use, Chemical Use, and Biosolids Production for Sidestream Treatment Technologies with Thermal Hydrolysis[a]

	THP Baseline (No Sidestream Treatment)	THP + Sidestream Treatment with PAD	THP + Sidestream Treatment with Anammox
Energy Use			
Sidestream Treatment, kW	-	8	26
Methanol Feed, kW	7	-	-
Aeration Basins, kW	600	551	551
Anaerobic Digestion, kW[b]	65	65	65
Anaerobic Digestion Energy Generation, kW[c]	(648)	(635)	(638)
Net Energy, kW	24	(11)	4
Annual Energy Consumption, kWh/yr	210,000	(100,000)	40,000
Annual Energy Cost[d], $/yr	**$16,000**	**($8,000)**	**$3,000**
Energy Cost Compared to Baseline, $/yr		-$24,000	-$13,000
Energy Cost Compared to Baseline, %		-150.0%	-81.3%
Chemical Use			
Methanol Consumption, kg/d (lb/d)	943 (2,079)	-	-
Methanol Consumption, MG/yr (dry tons/yr)	344 (379)	-	-
Annual Methanol Cost[e], $/yr	**$168,000**	**-**	**-**
Biosolids Production			
Biosolids Production, kg/d (lb/d)	6,380 (14,065)	5,695 (12,555)	6,317 (13,927)
Biosolids Production, dry metric tons/day	6.4	5.7	6.3
Biosolids Production, wet metric tons/day[f]	22.8	20.3	22.6
Annual Land Application Cost[g], $/yr	**$446,000**	**$398,000**	**$442,000**
Cost Compared to Baseline, $/yr		-$48,000	-$4,000
Cost Compared to Baseline, %		-10.8%	-0.9%
TOTAL			
Total Estimated Annual Cost for Energy, Methanol, and Biosolids Beneficial Use, $/yr	**$630,000**	**$390,000**	**$445,000**
Total Cost Compared to Baseline, $/yr		-$240,000	-$185,000
Total Cost Compared to Baseline, %		-38.1%	-29.4%

[a] Values represent average annual conditions
[b] Energy requirements for THP are not listed in this table but are anticipated to be similar between the three alternatives.
[c] Assumes 600 BTU/ft3 and 35% energy efficiency
[d] Assumes $0.0768/kWh and assumes net energy generated could be sold at the same rate
[e] Assumes $443.89 per dry ton for methanol
[f] Assumes 28% TS for biosolids
[g] Assumes $53.65/wet metric ton, which is the sum of the biosolids hauling and biosolids beneficial land application costs listed in Table 2

The energy use, chemical use, and biosolids production data for the baseline and sidestream treatment technologies with THP, as shown in Table 11, in comparison to the baseline and sidestream treatment technologies without THP, as shown in Table 7, demonstrates some important observations. First, due to the resulting less energy required for nutrient removal in the aeration basins, both THP with PAD and THP with Anammox contribute to additional net energy savings compared to the THP Baseline (no sidestream treatment), which is a similar conclusion to these three treatment scenarios without THP.

Second, the energy requirement is significantly reduced for THP with PAD compared to PAD without THP because the enhanced volatile solids reduction in THP takes place upstream of PAD and results in almost half the solids loading to PAD which subsequently reduces the necessary PAD reactor volume, and associated energy requirements, by nearly half.

Finally, similar to the conclusion derived from Table 7, Table 11 demonstrates that THP with Anammox has no significant effect on biosolids production. In contrast, THP with PAD is anticipated to be capable of achieving nearly an 11 percent additional reduction in biosolids beyond the THP Baseline (no sidestream treatment). This amounts to a total of a 29 percent reduction in biosolids compared to the Baseline without THP (also no sidestream treatment).

The additional volatile solids reduction achieved from PAD occurs independent of the additional volatile solids reduction achieved from THP. This is because the additional volatile solids reduction attained from PAD is achieved from a different mechanism than THP. THP achieves additional volatile solids reduction by applying temperature and pressure to burst the cell walls of bacteria within the sludge. In contrast, PAD achieves additional volatile solids reduction because the bacteria and decay products that are not degradable under anaerobic conditions become degradable under aerobic conditions. These bacteria and decay products exist after anaerobic digestion regardless of whether or not THP is applied.

Integration of PAD and Anammox with Phosphorus Recovery

Phosphorus recovery targets the significant amount of phosphorus (as much as 40 percent of the influent load) that can be returned to the liquid treatment process from residuals treatment. By recovering the phosphorus in the recycle stream as struvite, the amount of phosphorus required for the liquid treatment stream to remove is reduced. Because neither PAD nor Anammox are designed for phosphorus removal, some considerations should be examined if PAD or Anammox are integrated into an overall sidestream treatment strategy which includes phosphorus recovery.

A phosphorus recovery system adds magnesium to the high strength nutrient liquor from anaerobic digestion to induce struvite precipitation. Typically, this is conducted on the recycle filtrate, and generally about 80 to 90 percent of the phosphorus is removed with 8 to 10 percent of the ammonia also removed in the struvite reaction. Once created, the struvite is captured and removed from the treatment system for further refinement and collection.

For Anammox to be incorporated with phosphorus recovery, Anammox should be located downstream of the phosphorus recovery process. Since both treatment processes are located on the dewatering filtrate stream, both processes would simply be operated in series. While the Anammox process is biological in nature, the phosphorus recovery is a chemical reaction. Since the chemical reactions are more efficient at higher concentrations, placing the phosphorus recovery upstream of the Anammox is imperative to ensure that the maximum amounts of ammonia and phosphorus are available to maximize the phosphorus recovery that can be achieved. While the amount of phosphorus should still be monitored to ensure that an adequate amount remains available for biological growth, the Anammox process produces little sludge which indicates that minimal phosphorus is required for this purpose.

Because the PAD process is located in the sludge stream and significantly reduces the ammonia before it becomes filtrate, utilization of PAD limits which phosphorus recovery process can be used. However, it does not mean that phosphorus recovery is not viable. At the time of this writing, there is at least one manufacturer who produces a phosphorus recovery system that operates in the sludge stream.

Discussion

Although the life cycle costs for the Baseline (No Sidestream Treatment), Sidestream Treatment with PAD, and Sidestream Treatment with Anammox were determined to be equivalent, it must be noted that these costs are representative for an entire greenfield water reclamation facility. A retrofit installation will most likely have different capital costs with the associated facilities but may have similar annual cost savings as presented in Table 7.

If equivalent life cycle costs are assumed, alternative reasons should be considered for selecting a treatment technology for the purpose of meeting strict nutrient effluent limitations. For example, PAD should be considered when nitrogen removal without the need for supplemental carbon or alkalinity is desired in addition to the desire for additional volatile solids destruction. Enhanced volatile solids destruction may be desired if biosolids hauling and/or land application or final utilization costs are high.

Anammox should be considered when nitrogen removal without the need for supplemental carbon or alkalinity is required in addition to the desire for energy minimization due to high energy costs or if there is a goal of energy neutrality at the water reclamation facility.

A full life cycle cost analysis of the two sidestream treatment processes with THP may favor PAD because the enhanced volatile solids reduction in THP taking place upstream of PAD results in a significant reduction of the necessary PAD reactor volume and associated energy requirements.

Conclusions

PAD and Anammox are both sidestream treatment technologies which are excellent options for the reduction of nitrogen recycled back to the liquid stream without the need for supplemental carbon or alkalinity. However, the unique differences between these two technologies should be considered when evaluating the best technology for a specific water reclamation facility.

The simulation model results confirmed that the effluent limitations could be achieved without the addition of supplemental carbon or alkalinity with either PAD or Anammox as sidestream treatments. The baseline condition could not achieve the effluent limitations without the addition of supplemental carbon.

Since PAD and Anammox sidestream treatment technologies target different sidestream flow streams (PAD targets digester effluent while Anammox targets the filtrate or centrate produced from dewatering), different performances are predicted by simulation results. Compared to Anammox, PAD achieves greater BOD, TSS, VSS, NH3, TKN, and TN destruction as measured by mass removal, due to the VSS destruction associated with PAD. Because of the additional VSS destruction, PAD result in significantly less predicted TSS, VSS, NH3, TKN, and TN in biosolids compared to the baseline or the Sidestream Treatment with Anammox. Anammox achieves greater TP removal than PAD, associated with the Anammox waste stream.

The model results confirm that both sidestream treatment technologies evaluated can remove significant amounts of constituents from the filtrate compared to the baseline (no sidestream treatment) while achieving similar effluent quality.

The energy used in either sidestream treatment technology results in less energy required for nutrient removal in the aeration basins. For Sidestream Treatment with Anammox, the energy saved in the aeration basins overcomes the energy required for sidestream treatment. Considering energy use, chemical use, and biosolids production, sidestream treatment with PAD demonstrates a net annual energy cost savings of 8.8 percent relative to sidestream treatment with Anammox and a net annual energy cost savings of 23.8 percent relative to the baseline (no sidestream treatment).

THP with PAD is anticipated to be capable of achieving nearly an 11 percent additional reduction in biosolids beyond the THP Baseline (no sidestream treatment), which amounts to a total of a 29 percent reduction compared to the Baseline without THP (also no sidestream treatment). This is due to the volatile solids reduction attained from PAD being achieved from a different mechanism than THP.

Because neither PAD nor Anammox are designed for phosphorus removal, some considerations should be examined if PAD or Anammox are integrated into an overall sidestream treatment strategy which includes phosphorus recovery.

Considering the full cost analysis, the Baseline (No Sidestream Treatment) offers the lowest capital cost due to the required construction of sidestream treatment facilities as compared to constructing a methanol feed and storage facility. Sidestream Treatment with PAD offers the lowest annual cost primarily due to the significant savings in biosolids hauling and land application due to the VSS destruction associated with PAD. The lowest 20-year net present value is equivalent for all three alternatives. Thus, PAD should be considered when nitrogen removal without the need for supplemental carbon or alkalinity is desired in addition to the desire for additional volatile solids destruction. Anammox should be considered when nitrogen removal without the need for supplemental carbon or alkalinity is desired in addition to the goal of energy minimization.

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