

BIOSOLIDS MINIMIZATION USING INTEGRATED ALKALINE SLUDGE HYDROLYSIS AND BIOLOGICAL NUTRIENT REMOVAL PROCESS

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ABSTRACT

This paper presents a pilot-scale evaluation of an integrated approach to sludge management utilizing a combination of biological nutrient removal and biosolids alkaline hydrolysis, as well as attempts to explore the impact of recycled alkaline hydrolysates on sludge yield and anaerobic digestion. The novel concept of converting an existing conventional activated sludge (CAS) wastewater treatment plant in St. Marys, Ontario to BNR and integrating it with Lystek technology emerged to reduce sludge production and spare the plant expansion of its sludge storage facilities. In the integrated sludge management strategy, first waste activated sludge (WAS) from the BNR system is treated with Lystek technology and thereafter a portion of the Lystek-treated sludge is recycled to the BNR system and the primary digester, and the remaining sludge is pumped to storage/land application.

A pilot study was undertaken to demonstrate the effectiveness of the proposed BNR system and to assess the impact of recycling Lystek-treated sludge to the BNR system and anaerobic digester. The pilot plant produced effluent comparable to that of the full-scale plant with biological nitrification/denitrification and phosphorous removal. The addition of Lystek-treated sludge did not have a detrimental effect on the pilot plant treatment efficiency. Anaerobic respirometric studies of pilot plant WAS with the addition of Lystek-treated sludge indicated increased VSS destruction, COD removal, and methane production. At a similar SRT, the pilot plant observed yield was 0.37 gTSS/gCOD, compared to 0.66 gTSS/gCOD for the full-scale system. When combined with Lystek treatment and recycle, the integrated sludge management strategy is expected to achieve an estimated 84% reduction in volumetric sludge disposed from the site.

KEYWORDS

biological nutrient removal, alkaline sludge hydrolysis, phosphorous, biosolids, sludge yield

INTRODUCTION

Restricted land availability, increasingly stringent environmental regulations, and high treatment and disposal costs have pushed biosolids management to the forefront of today's environmental

issues. Several sludge treatment technologies have been explored in the past to improve biosolids management through enhanced stabilization and dewatering, including heat treatment, chemical treatment, and mechanical disintegration (Neyens *et al.*, 2003a). Thermo-chemical treatment by sulfuric acid at 121 °C has been demonstrated to achieve 70-80% solubilization of TSS (Yang and Gaudy, 1974). Muller (2001) evaluated several disintegration methods including temperature in the 40-180 °C range, chemical treatment with acids, alkalis, and ozone, and mechanical disintegration methods using ultrasounds, and mills. The work of Higgins and Novak (1997) has clearly elucidated the positive role of cations in sludge settling and dewatering. In fact, Erdinçler and Vesilind (2000) have shown that treatment of biological sludge with sodium hydroxide for 45 minutes significantly improved dewaterability. Similarly, Neyens *et al.* (2003b) achieved greater than 60% dry solids in filter cakes of sludge pretreated with sulfuric acid at 120-160 °C for 1 hr. Alkaline hydrolysis with lime at pH 10 and temperature of 100 °C for 1 hour was observed to increase cake solids from 28% to 46% (Neyens *et al.*, 2003a). While the impact of both acid and alkaline hydrolysis of sludges on dewaterability has already been explored, the overall integration of sludge treatment technologies with liquid wastewater treatment systems has received little attention.

Biomass growth on cell lysis products, known as cryptic growth, has been sparsely addressed in the literature. Furthermore, the impact of recycled cell lysis products, or hydrolysates, has not been studied. Yasui *et al.* (1996) have used ozonation of a third of the return activated sludge prior to recirculation to the aeration tank to reduce waste activated sludge. Similarly, Rocher *et al.* (2001) have found that the bacterial yield in chemostat reactors treating acetate with waste activated sludge alkaline hydrolysate (at pH 10, 60 °C for 20 minutes) was 37% lower than conventional activated sludge. Thus, this paper presents pilot-scale evaluation of an integrated approach to sludge management utilizing a combination of biological nutrient removal and biosolids alkaline hydrolysis, as well as attempts to explore the impact of alkaline hydrolysates on sludge yield and anaerobic digestion.

PROJECT BACKGROUND

The primary driver for this project has been the need for extended sludge storage facilities at the St. Marys Wastewater Treatment Plant (WWTP) in St. Marys, Ontario. The plant is a conventional activated sludge (CAS) plant, employing primary clarification (with WAS co-thickening), with a rated capacity of 5,560 m³/d. Lystek International Inc. (Lystek) of Waterloo, Ontario, has developed a process involving the application of heat, alkalization and high-shear mixing to render dewatered biosolids completely pumpable with conventional pumps, while retaining their high solids concentration, hence facilitating agricultural land application of dewatered sludge. Thus, the novel concept of converting the existing CAS WWTP in St. Marys to BNR and integrating it with Lystek technology emerged to reduce sludge production and spare the plant expansion of its sludge storage facilities.

OVERVIEW OF LYTEK

The Lystek process is an innovative biosolids treatment and processing technology that has been successfully developed over 3 years at bench- and pilot-scales, and further tested at full-scale at the Guelph WWTP in Guelph, Ontario. The process involves the application of heat (65-70 °C),

alkalization with potassium hydroxide, and high-shear mixing of dewatered sludges in a batch or semi-continuous system to achieve a high solids concentration (15-20 % by weight), pathogen-free, and nutrient-rich liquid biosolids product that meets U.S. EPA criteria for Class A biosolids to be used in agricultural land application (Singh *et al.*, 2006). The process also reduces the viscosity of dewatered sludges from greater than 2 million centipoises (cP) to less than 4,500 cP, and renders dewatered and processed biosolids completely pumpable with conventional pumps.

Analyses of Lystek-treated sludge from the full-scale demonstration plant located in Guelph, Ontario are summarized in Table 1. The analyses indicate that the Lystek hydrolysate is characterized by extremely high TSS, VSS, TCOD, SCOD, and moderately high TKN and TP. A metals analysis of the Lystek-treated sludge, summarized in Table 2, indicates that the principal metals are Al, Ca, Mg, Na, K, and Fe, with fairly high concentrations of soluble Al and Fe. Most metals originate from industrial wastewater treated at the Guelph WWTP.

Table 1 - Characteristics of Lystek Sludge

Parameter	Sample 1	Sample 2
Viscosity (cp)	3,600	4,500
pH	11	9.5
TSS (g/L)	109	111
VSS (g/L)	74	80
BOD (g/L)	–	–
SBOD (g/L)	–	–
COD (g/L)	191	186
SCOD (g/L)	65	60
NH₄-N (mg/L)	150	240
NO₃-N (mg/L)	72	54
NO₂-N (g/L)	–	–
TKN (g/L)	8.7	8.4
STKN (g/L)	7.2	6.7
TP (g/L)	1.2	1.3
SP (PO₄-P) (g/L)	1.2	1.1
VFAs (mg/L)		
Acetic Acid	730	840
Propionic Acid	220	200
Iso-butyric Acid	–	92
Valeric Acid	–	76

Table 2 – Metal Analysis of Lystek Sludge

Metal (mg/L)	Total Metals	Soluble Metals
Aluminum (Al)	100	68
Calcium (Ca)	711	440
Cadmium (Cd)	0.04	0.01
Cobalt (Co)	0.19	0.06
Chromium (Cr)	1.8	1
Magnesium (Mg)	98	68
Manganese (Mn)	13	–
Sodium (Na)	225	215
Nickel (Ni)	0.51	0.1
Lead (Pb)	1.09	–
Potassium (K)	423	160
Zinc (Zn)	27	8
Iron (Fe)	600	80
Copper (Cu)	20	4

INTEGRATION OF BNR AND LYSTEK TECHNOLOGIES

The conceptual design for the integrated thermal alkaline sludge hydrolysis and biological nutrient removal technologies is shown in Figure 1. The conceptual design comprises two primary sections, biological treatment and sludge management. Biological treatment, or BNR, consists of anoxic tanks, aeration tanks, and secondary clarifiers in a Modified Ludzak-Ettinger (MLE) configuration, complete with internal recirculation (IR), return activated sludge (RAS), and waste activated sludge (WAS). Effluent from the secondary clarifiers undergoes ultra-violet (UV) disinfection, while WAS is sent for sludge management.

The sludge management strategy includes WAS thickening, digestion, dewatering, Lystek, and phosphorous removal, as well as a number of recycle streams. WAS is thickened to approximately 3.0 % (by weight) prior to undergoing primary and secondary digestion. Digested sludge is then dewatered to approximately 14 % before Lystek treatment. Lystek-treated sludge is stored or recycled in the following manner:

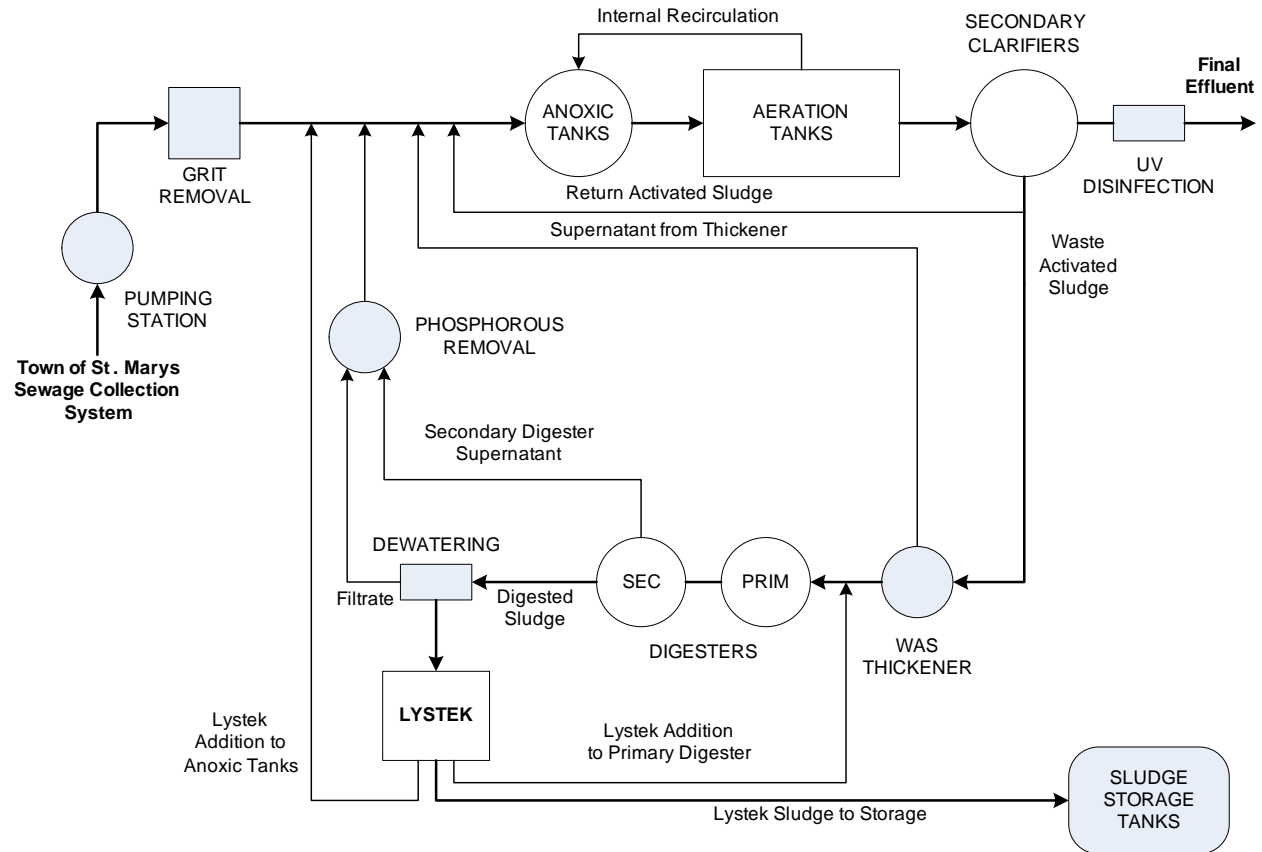
- A portion of the Lystek sludge is recycled to the BNR system;
- A portion is recycled to the primary digester; and
- The remaining sludge is pumped to storage and/or disposal.

At current full-scale plant flow at the St. Marys WWTP, it is anticipated that approximately 6 m³/d of Lystek sludge will be produced, of which approximately 2.8 m³/d will be recycled to the BNR system and 2 m³/d will be recycled to the primary digester.

Other recycle streams include thickener supernatant, secondary digester supernatant, and dewatering filtrate. It is anticipated that phosphorous taken up during BNR processes will be subsequently released in soluble form under anaerobic conditions found in the primary digester.

Hence, the secondary digester supernatant and dewatering filtrate will require chemical phosphorous removal to prevent phosphorous from accumulating within the BNR system

Figure 1 - Conceptual Design for Minimizing Biosolids Using Integrated Alkaline Sludge Hydrolysis (Lystek) and Biological Nutrient Removal Process.



PILOT PLANT STUDY

Pilot Plant Design

The objective of the pilot study was to demonstrate the effectiveness of the proposed BNR system and to assess the impact of recycling Lystek-conditioned sludge to the biological treatment system on anaerobic digestion. The viability of the overall approach hinges on the reduction in sludge production upon conversion from CAS to BNR, as well as the potential for recycle of the hydrolysates. The main uncertainty was the impact of the hydrolysates on the efficiency of the BNR process. In order to compare the pilot plant performance to the existing full-scale plant, the aerobic hydraulic retention time (HRT) of the pilot plant was set equal to that of the full-scale plant. Based on the design flow of 5,560 m³/d and aeration tanks with a volume of 2,457 m³, the aerobic HRT of the full-scale plant is 10.6 hr. To maintain similar HRT in the pilot aeration tank of 4 m³ and taking into consideration internal recirculation and return activate sludge, an equivalent influent flow of 9.1 m³/d was required.

A detailed schematic of the experimental setup of the MLE system is shown in Figure 2. The MLE system consisted of an anoxic reactor and aerobic reactor with volumes of 1 and 4 m³, respectively, as well as a clarifier with a volume of 1.4 m³. The raw sewage was introduced in the anoxic reactor along with internal recirculation (IR) and return activated sludge (RAS) from the clarifier. The anoxic reactor was continuously mixed using an overhead mixer (SEW Eurodrive, Type FAF37, 0.33 hp). The mixed liquor from the anoxic reactor flowed to the aerobic reactor by gravity. A portion of the mixed liquor from the aerobic reactor was recycled back to the anoxic reactor (internal recirculation) for biological denitrification and to maintain biomass concentration within the system. Air was introduced at the bottom of the aeration tank using stainless steel coarse bubble diffusers (Sanitaire, Model # D24) to maintain the required dissolved oxygen (DO) concentration and to mix the tank contents. Air to the aeration tank was supplied from a line branched from existing blowers at the WWTP. A globe valve was used to maintain a pressure of approximately 3 to 4 psig in the airline to the pilot aeration tank. The mixed liquor from the aeration tank was then transferred to the clarifier by gravity for physical solids separation. Sludge was wasted from the return activated sludge line to maintain the desired solids retention time (SRT).

A peristaltic pump (Verder Ltd., Model # Verderflex VF25, 1.5 hp, 230/1/60) was used to transfer the raw sewage to the anoxic tank. Progressive cavity pumps (Liberty Process Equipment Inc., Model # APM33, 0.5 hp, 230/3/60, 1725 rpm) with variable frequency drives were used to transfer IR, RAS, and waste activated sludge (WAS). The anoxic and aerobic reactors were equipped with an online oxidation-reduction potential (ORP) sensor (Aquametrix, Model # R60C-6-1; Controller Model # 2200R-1-A) to monitor ambient oxidative/reductive conditions in the tanks. The aeration tank was also equipped with an online DO sensor (Aquametrix, Model # P91, Controller 2200D-1-A) to monitor DO concentration and a mixed liquor suspended solids (MLSS) sensor (Aysix Technologies, Model # A6-15) to monitor MLSS concentration in the aeration tank.

Pilot Plant Operating Conditions

Pilot plant operation was initiated with a design influent flow of approximately 9.1 m³/day. The pilot plant was operated for about 18 days at an SRT of 5 days and 51 days at an SRT of 8.2 days. Operation of the plant was later changed with the addition of Lystek sludge to the anoxic tank at a rate of 0.055% (Phase I) and 0.088% (Phase 2) of the influent flow. The pilot plant was operated a further 41 days during Lystek Phase I and for 23 days during Lystek Phase 2 at an 8.2-d SRT. It should be noted that the pilot plant SRT of 8.2 d was comparable to that of the full-scale and hence this period was used to compare the pilot plant performance (with and without Lystek) to the full-scale plant results. The pilot plant various operating conditions are shown in Table 3.

Table 3 – Operating Parameters of MLE Pilot Plant

	Without Lystek Sludge (SRT = 8.2 d)	With Lystek Sludge (Lystek Phase I)	With Lystek Sludge (Lystek Phase II)
Influent, Q (m ³ /d)	8.9	8.6	13.8
Internal Recirculation, IR (m ³ /d)	21.9	17.5	23.2
RAS (m ³ /d)	9.3	7.9	13.1
HRT (hr)*	17.3	17.9	11.1
SRT (d)	8.5	9.4	9.4

* HRT is based on the influent flow rates.

Sampling and Monitoring

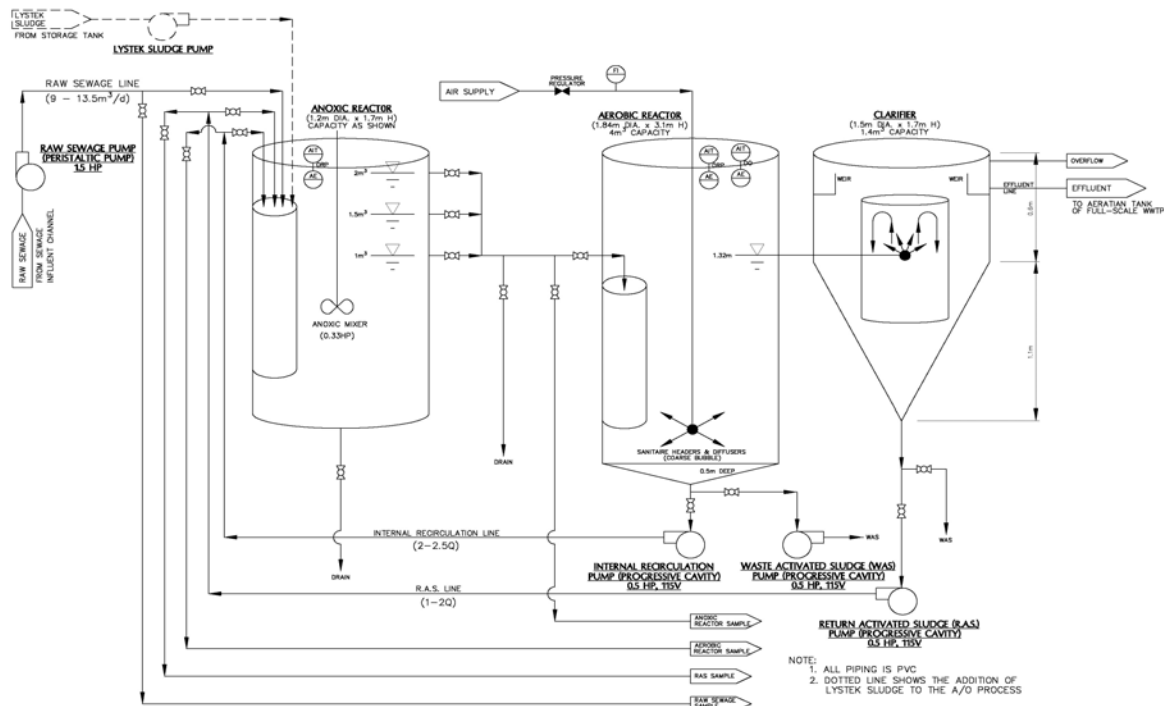
Samples of raw sewage to the pilot plant, anoxic tank effluent, aeration tank effluent, clarifier effluent, return activated sludge and internal recirculation were collected three times per week throughout the pilot plant study. All streams, with the exception of return activated sludge and internal recirculation were analyzed for TSS, VSS, total BOD₅ (TBOD₅), soluble BOD₅ (SBOD₅), total COD (TCOD), soluble COD (SCOD), total Kjeldahl nitrogen (TKN), soluble TKN (STKN), ammonia, nitrates, nitrites, total phosphates (TP), soluble phosphates (SP), volatile fatty acids (VFA), alkalinity, sulfates, and chlorides. Return activated sludge and internal recirculation were analyzed only for TSS and VSS. In addition to the regular weekly samples, 4-hour composite samples of the raw influent wastewater were collected occasionally and analyzed for TCOD, SCOD, TBOD, SBOD, TSS, VSS, TKN, STKN, ammonia, and TP.

Tests on sludge volume index (SVI), oxygen uptake rate (OUR) and zone setting velocity (ZSV) for the pilot and full-scale plant were performed regularly.

For the full-scale plant, grab samples of the primary effluent, aeration tank effluent, and final clarifier effluent were collected three times per week along with the pilot plant samples. Primary effluent samples were analyzed for TBOD, SBOD, TCOD, SCOD, TKN, STKN, and alkalinity, while samples of the full-scale aeration tank and clarifier were analyzed for TP and SP in addition to the aforementioned parameters.

In addition, aerobic respirometry studies with Lystek hydrolysates as the sole carbon source and combined with raw sewage were undertaken to characterize sludge and determine biokinetic coefficients. Anoxic denitrification tests were also conducted. Furthermore, three laboratory-scale fed-batch mesophilic completely-mixed anaerobic digesters were operated for approximately 100 days at an SRT of 15 d on primary full-scale sludge, thickened WAS from the pilot A/O system with and without Lystek hydrolysate.

Figure 2 - Schematic of MLE process with the addition of Lystek Sludge



**FIGURE 1: A/O (MLE) SYSTEM PROCESS FLOW DIAGRAM
ST. MARYS WWTP - PILOT STUDY
TOWN OF ST. MARYS**

RESULTS AND DISCUSSION

The pilot plant effluent quality during various phases of operation is summarized in Table 4. The table includes effluent quality for biological treatment without Lystek addition, and with Lystek addition at 0.055% and 0.088% (by volume) of pilot plant influent flow. It is evident that recycling Lystek sludge to the BNR system was not detrimental to its treatment efficiency. Effluent quality for each phase was very comparable. Similarly, sludge settleability was comparable, with observed zone settling velocities of 70-80 m/d prior to hydrolysate addition and 65-85 m/d afterwards.

Nitrification efficiency was not impacted by the addition of Lystek hydrolysates, as reflected in the low effluent ammonia concentrations of approximately 0.5 mg/L. Interestingly, effluent nitrates increased marginally by 1.7 mg/L to 4.2 mg/L.

Table 4 - Comparison of Effluent Quality: Without Lystek and With Lystek

Parameter (mg/L)	Without Lystek Sludge (SRT = 8.2 d)	With Lystek Sludge (Lystek Phase 1)	With Lystek Sludge (Lystek Phase 2)
TSS	15.7 ± 3.8 (20)	21.1 ± 8.5 (17)	16.7 ± 5.0 (7)
VSS	10.9 ± 2.6 (20)	15.8 ± 6.2 (17)	12.7 ± 3.7 (6)
BOD	18.5 ± 4.4 (22)	20.0 ± 3.5 (17)	16.7 ± 9.1 (3)
SBOD	12.2 ± 3.5 (22)	9.9 ± 2.0 (17)	3.7 ± 2.9 (3)
COD	36.7 ± 9.4 (22)	44.7 ± 10.7 (17)	56.4 ± 13.8 (7)
SCOD	26.8 ± 6.5 (22)	29.1 ± 7.3 (17)	29.3 ± 6.0 (7)
NH ₄ -N	<0.4	0.5 ± 0.1 (17)	<0.4
NO ₃ -N	2.5 ± 1.9 (22)	4.2 ± 1.4 (15)	4.5 ± 1.5 (4)
NO ₂ -N	<0.3	0.6 ± 0.4 (17)	0.6 ± 0.5 (4)
TKN	6.4 ± 2.4 (20)	6.8 ± 2.1 (16)	1.3 ± 0.6 (3)
STKN	4.8 ± 2.5 (20)	2.9 ± 2.2 (16)	1.2 ± 0.6 (3)
TP	0.9 ± 0.8 (22)	0.8 ± 0.4 (17)	0.6 ± 0.7 (4)
SP (PO ₄ -P)	<0.3	<0.3	<0.3
Alkalinity	321 ± 30 (18)	330 ± 47 (17)	–
Chlorides	692 ± 51 (22)	379 ± 142 (11)	–

The results of the denitrification studies, depicted in Figure 3, clearly indicate that the Lystek hydrolysates were high in readily biodegradable COD (RBCOD), with biomass specific denitrification rates matching those of acetate. Furthermore, aerobic respirometry revealed that RBCOD in the hydrolysates was 11,000 mg/L or 17% of the SCOD. At the maximum projected hydrolysate recirculation rate, both the yield and maximum heterotrophic growth rates were unaffected by the hydrolysates, with respective values of 0.49 gVSS/gCOD, and 9.4 d⁻¹.

Anaerobic respirometric studies of thickened pilot plant WAS with added Lystek hydrolysates affected 21% and 40% increases in anaerobic VSS destruction and COD removal efficiencies, respectively, relative to thickened pilot plant WAS alone. Also, methane production was increased by 90%. The increased VSS destruction, COD removal, and methane production were observed despite a 40% increase in COD loading. Continuous-flow anaerobic digestion studies confirmed that at steady-state, the addition of the Lystek hydrolysate affected a 21% increase in VSS destruction efficiency and a 30% increase in overall COD removal.

The observed yields for the full-scale plant and pilot plant during various phases of operation were calculated from graphs of cumulative TSS produced versus COD removed (not shown). The results are summarized in Table 5. The yield of the BNR pilot plant at an SRT of 8.2 d was 0.37 gTSS/gCOD (R²=0.99) versus a yield of 0.66 gTSS/gCOD for the full-scale system, a 44% reduction. Sludge yield reductions ranged from 27 to 48% for other phases of operation. It is evident from Table 5 that recycling Lystek-treated sludge to the anoxic tank of the biological treatment system resulted in only a small increase yield, which could possibly be attributed to other operating conditions.

Figure 3 - Denitrification with Lystek Hydrolysate

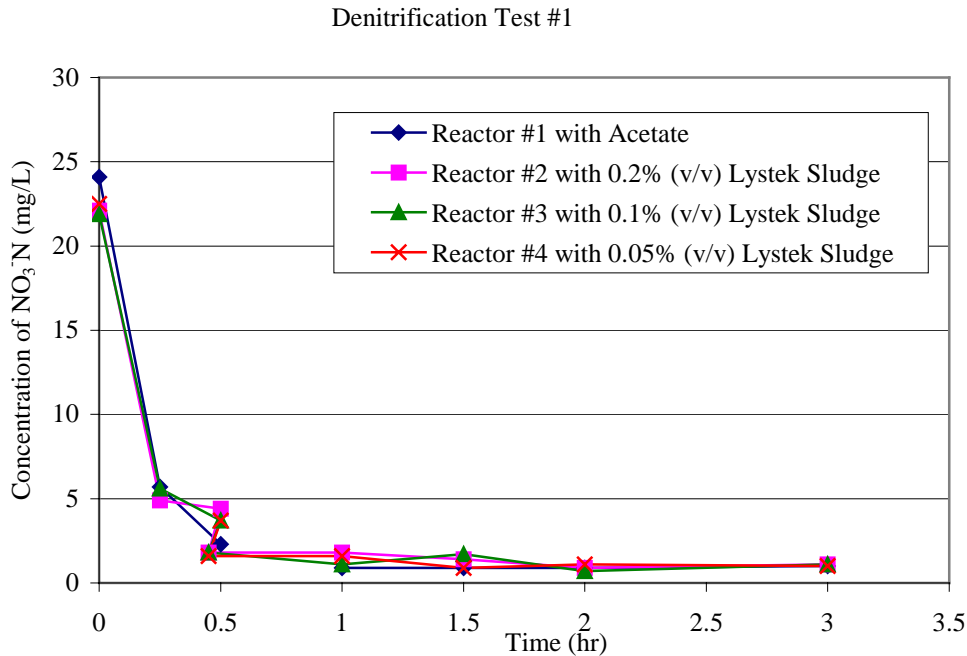


Table 5 – Observed Yields of Full-Scale and Pilot Plant

<i>Parameter</i>	<i>Full-Scale</i>	<i>Pilot Plant</i>	
		<i>SRT = 8.2 d</i>	<i>with Lystek Addition</i>
Size, m ³	2,457	5.0	5.0
Average Flow, m ³ /d	4,150	9.0	7.5
HRT, hr	14.2	13.3	16.0
SRT, d	6.5	8.2	9.4
Observed Yields, gTSS/gCOD	0.64	0.33	0.40
gTSS/gBOD	1.44	0.86	0.87

OVERALL IMPACT OF INTEGRATED APPROACH

Table 6 presents a comparison of the various sludge quantities generated by the integrated BNR-alkaline hydrolysis system relative to the existing conventional plant. It should be noted, that although the plant currently does not employ sludge dewatering, in order to ensure fair comparative assessment, dewatering which is integral to the Lystek process has also been included in the conventional system. It is apparent from Table 6 that the integrated approach achieves an estimated 84% volumetric sludge reduction in the final quantities of sludges disposed from the site. While the BNR by itself is responsible for about 44% volumetric and

mass reductions, the enhanced anaerobic digestion efficiency and the recirculation of Lystek-processed sludges affected an equal contribution to overall sludge reduction.

Table 6 - Comparison of Overall Sludge Generation
(all units are in m³/d except where stated)

Parameter	Integrated BNR-Lystek Process	Conventional Activated Sludge Process with Dewatering
Design Flow	5,560	5,560
Influent COD, mg/L	700	700
Sludge yield, gTSS/gCOD	0.37	0.66
Volatile fraction, %	75	75
WAS, kgVSS/d	1,090	1,940
WAS, kgTSS/d	1,450	2,590
WAS (0.8% dry solids)	180	325
Thickened WAS (3.5% solids)	41	74
VSS destruction in digester, %	50	40
Digested sludge solids, %	4	4
Digested sludge flow	22.5	45
Dewatered sludge flow (15% sol.)	6.4	12.8
Lystek Sludge flow (14% sol.)	6.9	N/A
Recycled Lystek to BNR	2.8	N/A
Recycled Lystek to Digester	2	N/A
Disposed Sludge	2.1	12.8

BENEFITS OF LYTEK SLUDGE

In addition to the reduced BNR sludge yield, the integrated Lystek technology provides the following benefits (Singh *et al.*, 2006):

- Conversion of regular dewatered biosolids to high-solid content, nutrient-rich and pathogen-free US EPA 'Class A' biosolids;
- Processed material with a high biosolids concentration (15-20 % by weight) retains pumpability for effective handling using conventional liquid pumping equipment, as a result of the viscosity reduction from greater than 2,000,000 cP in dewatered biosolids to less than 5,000 cP in processed material;
- Elimination of pathogens such as *Escherichia coli*, fecal coliforms, *Salmonella*, enteric viruses and helminthes with no re-growth over 2 years of storage at ambient temperature;
- Small foot print of the Lystek system at the back end of the WWTP and easy integration into an existing WWTP operation;
- Low capital and operating costs; and
- Classification of Lystek hydrolysates as a fertilizer product by the Canadian Food Inspection Agency, with 40% higher organic fertilizer value than regular biosolids.

CONCLUSIONS

Pilot-scale testing coupled with laboratory testing confirmed the reduction in sludge production by the BNR process, as well as the absence of any adverse impacts on recycling of the hydrolysates to the BNR process and a beneficial impact on anaerobic digestion. Thus, the implementation of the developed concept will result in a disposed sludge volume of only 0.038% of the processed medium-strength municipal wastewater volume. Relative to a conventional activated sludge system with dewatering, this integrated BNR-alkaline sludge hydrolysis approach has the potential to reduce dewatered sludge disposal volumes by 84%.

ACKNOWLEDGMENTS

The authors wish to thank the Town of St. Marys and operators of the St. Marys WWTP for their support and cooperation during the pilot plant study.

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