Performance of Temperature-Phased Anaerobic Digestion (TPAD) System Treating Dairy Cattle Wastes

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Abstract

The performance of Temperature-Phased Anaerobic Digestion (TPAD) system in the stabilization of dairy cattle wastes at high solids concentrations has never been evaluated, though the process has been established as a feasible alternative to conventional mesophilic processes for the treatment of municipal wastewater sludges. The TPAD system, operating at a retention time of 14 days, was subjected to varying total solids (3.46 – 14.54%) and volatile solids (2.62 – 10.78%) concentrations of dairy cattle wastes. At total solids concentrations less than 10.35% corresponding to a system volatile solids loading of 5.82 g VS/L/d, the system achieved VS removals in the range of 37.8 – 42.6%. The maximum VS destruction of 42.6% was achieved at a total solids concentration of 10.35%. There was a drop in the system performance with respect to VS removal and methane recovery at total solids concentrations higher than 10.35%. For all total solids concentrations studied, the indicator organism counts in the biosolids were within the limits specified by U.S. EPA in 40 CFR Part 503 regulations for Class A designation.

Key Words: Anaerobic, Biosolids, Dairy Cattle, Class A, Temperature-Phased, Thermophilic

1. Introduction

Growing awareness of environmental damage and public health concerns has led to the implementation of more stringent environmental regulations, controls and policies on the disposal of wastes with a shift in emphasis from "What has been taken out?" to "How much is left?" The public interest in environmental quality makes waste management technology a critical consideration and waste generators are forced to adopt efficient and reliable waste treatment processes that produce more-stable, less-odorous biosolids; and reduce pathogens. Moreover, with the dwindling supply of fossil fuels, it is inevitable that we will have to find an environmentally sustainable alternative energy source if humankind is going to have a future on this planet. Thus, there is a need to move beyond regulatory compliance and secure the energy future.

The quest for efficient waste treatment processes and cleaner forms of energy has stimulated interest in anaerobic digestion. Anaerobic digestion is no longer seen merely as a complementary process augmenting aerobic treatment but has become an established and proven technology demonstrating great flexibility in treating different types of waste streams, ranging from wet to dry and from clean organics to "grey" waste. It offers substantial cost benefits from reduced waste biomass accumulation, lower nutrient and energy requirements. Anaerobic digestion plays a dual role in waste treatment converting organic wastes into stable organic soil conditioners or liquid fertilizers and reducing the environmental impact of organic wastes prior to their disposal. In addition to the pollution-control role, anaerobic digestion is often regarded as a source of renewable energy in the form of methane gas. Thus, anaerobic digestion is seen as a process than can convert a disposal problem into a profit center.

Not all waste streams are amenable to anaerobic digestion, the process can degrade only organic materials. Researchers have exploited varied feedstocks that range from municipal and commercial wastes to agricultural residuals for anaerobic digestion. In many countries, agricultural wastes, the manures and crop residues that are derived from food production, are the largest source of wastes. The best use of these wastes is land application for nutrient recycling to crops, but lack of adequate land for optimum nutrient use and odor control has necessitated the need for suitable treatment and disposal methods. Conversion of agricultural residuals — animal manure in particular — into a renewable energy resource has been the focus of intensive research for more than two decades. Where costs are high for agricultural or animal waste disposal, and the effluent has economic value, anaerobic digestion and biogas production can reduce overall operating costs.

A broad array of anaerobic digestion systems has been studied for the treatment of livestock manures. Majority of these anaerobic digestion systems operates at mesophilic temperatures (35-40^{o}C). Though effective in reducing the organic content of wastes, studies have reported the survival of pathogenic bacteria at mesophilic temperatures [6]. The recently implemented 40 CFR Part 503 federal regulations, which classify biosolids as Class A or Class B based on the density (numbers/unit mass) of pathogens, restrict the land application or surface disposal of biosolids based on pathogen destruction criteria [13]. The mesophilic anaerobic digestion systems can achieve only limited destruction of pathogens restricting the use of biosolids from the process, significantly affecting the sustainability and cost effectiveness of the process. Moreover, the recalcitrant organics in livestock manures may only be partially degraded at mesophilic temperatures. There is a need for new and improved facilities if the biogas potential of the waste streams is to be fully realized. Of late, there has been a "renaissance of digestion", waste treatment facilities have shown widespread interest in upgrading the performance of anaerobic digestion systems to handle difficult-to-digest feed solids more effectively, increase digester loadings, and improve operating economies by my increasing volatile solids removal [10].

Among the innovative advanced digestion systems, the Temperature-Phased Anaerobic Digestion (TPAD), a patented process developed by Dr. Richard Dague and coworkers at Iowa State University (ISU), holds much promise. The TPAD is a two-stage anaerobic digestion system, which consists of two completely mixed reactors in series, operated at higher thermophilic temperature (typically 55^{o}C) in the first stage and lower mesophilic temperature (commonly 35^{o}C) in the second stage. Laboratory studies on wastewater sludges suggested that the TPAD process could achieve improved pathogen destruction, volatile solids removal, and gas production compared to conventional mesophilic digestion [3]. Since its development in the mid nineties, more than twenty full-scale TPAD systems have been set up in the United States for the treatment of wastewater sludges. In spite of having marked advantages over many high-rate single stage mesophilic systems in the treatment of municipal wastewater sludge, the performance of TPAD in the digestion of livestock manures has never been evaluated. Can we present a viable solution to the waste disposal problems associated with agribusiness in the form of TPAD technology? Bench-scale studies conducted at ISU Environmental Laboratory sought to address this question.

2. Materials and Methods

2.1 Substrate: Source and Characteristics

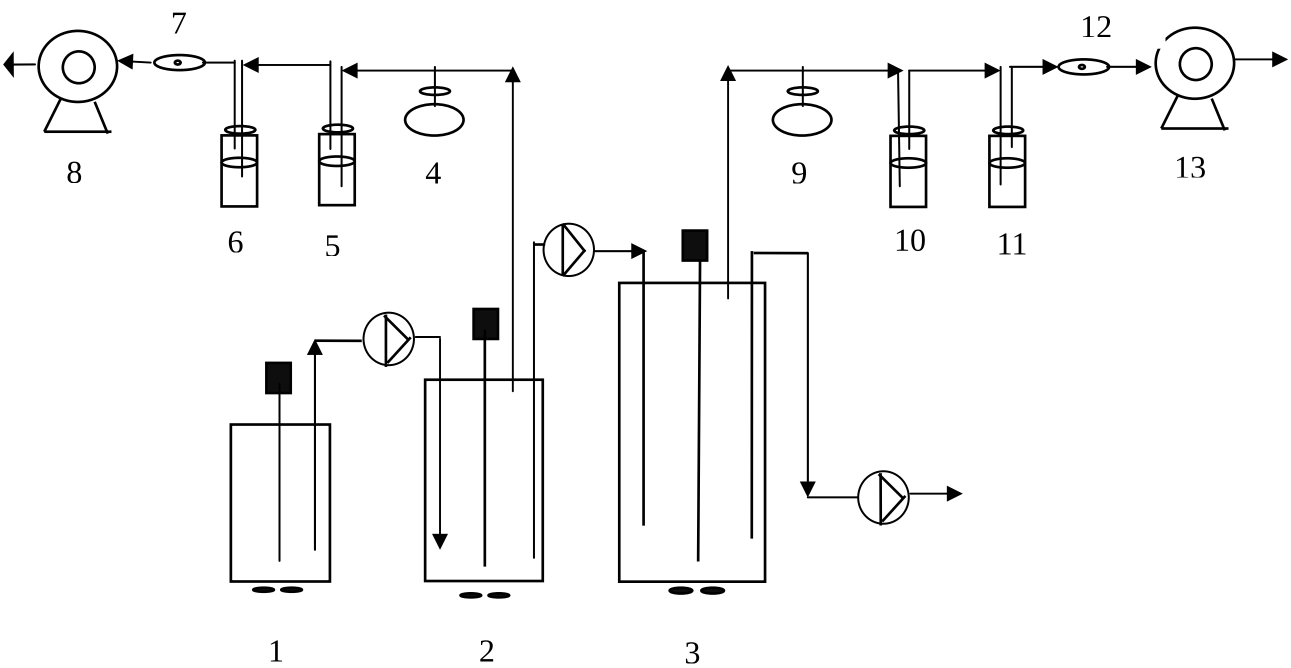
Dairy manure (feces and urine) from cows weighing over 1000 lbs was obtained on a bi-weekly basis from the Iowa State University Dairy. The high grain-finishing ration fed to the cattle is summarized in Table 1. Manure scraped off concrete floored pens had a total solids concentration of 16 ± 1%. Prior to use, the manure was mixed with the desired quantity of dilution water and macerated in a blender for 15 – 20 minutes. This was done to reduce potential clogging of the digester tubing. [2] have also reported maceration as a physical means of reducing the association of lignin with biodegradable cellulosic fraction of biofibers thereby improving the substrate accessibility to bacteria. It is also one of the easier options to implement in full-scale plants. The blended wastes were stored in a refrigerator until use to minimize substrate decomposition.

Table 1. Summary of cattle ration

Constituent	Quantity (Kg/d)
Alfalfa Silage	11.5 – 17.5
Corn Silage	9.0 – 11.5
Corn Glut	6.5 – 9.0
Corn Grain Ground	4.5 – 9.0
Soybean Meal	2.0 – 2.7
Cotton Seed with Lint	1.5 – 2.5
Lactating Mineral	0.5 – 1.0
Alfalfa Hay	3.5 – 4.5

2.2 Experimental Setup

Two bench-scale cylindrical Plexiglas ™ reactors fabricated in the Chemistry Machine Shop at Iowa State University were used in the study. The 20-L capacity first stage thermophilic reactor had a working volume of 12 L and the 30 L second stage mesophilic reactor had a working volume of 18 L. The reactors had ports for installation of the mixer, feeding, decanting, gas release and sampling. In order to improve mixing, each reactor had four 1.3-cm baffles running along the height of the reactor. The gas collection system consisted of a gas reservoir, a gas observation tube, a hydrogen sulfide scrubber with steel wool as the scrubbing medium, a gas sampling port and a wet-tip gas meter. The reactor system was operated in a constant temperature room maintained at 38 °C. The first stage thermophilic reactor was set up in a 58 °C water bath with a Fisher Isotemp 2100 (Fisher Company, Pittsburgh) immersion circulator. Figure 1 shows a schematic of the experimental set-up.



1 *Feeding Tank*
2 *Thermophilic Reactor*
3 *Mesophilic Reactor*
4, 9 *Gas Bags*
5, 10 *Gas Indicators*
6, 11 *Sulfide Scrubbers*
7, 12 *Gas Sampling Ports*
8, 13 *Gas Meters*

Figure 1. Schematic of the TPAD system

2.3 Start-up and Operation

The thermophilic and mesophilic reactors were seeded with 10 L of actively digesting sludge from an ongoing bench scale thermophilic reactor at ISU environmental lab and a full scale mesophilic swine waste digester (Nevada, IA), respectively. The reactors were then filled to their respective working volumes of 12 L and 18 L with hot tap water and purged with methane gas. The reactor contents were maintained at the respective temperatures for a week to allow temperature equilibration and utilization of substrate contained in the seed.

The TPAD system was operated in a semi-continuous mode feeding and collecting samples at 4-hour intervals of time (6 times daily). The effluent from thermophilic reactor was discharged to the mesophilic reactor followed by pumping of fresh feed into the thermophilic reactor. Effluent was withdrawn from the reactors 5 minutes prior to feeding to avoid the possibility of short-circuiting. The contents of the two reactors were mixed for 10 minutes every 30 minutes and temperature of the digesting sludge was monitored daily.

The TPAD system was operated at a 14-day retention time with the thermophilic unit conducted at 4-days and the mesophilic unit at 10-days. This was founded on the studies of [4], who suggested an optimum system retention time of 11-17 days for TPAD systems treating wastewater sludges. Single-stage systems studied by [5] for the treatment of cattle wastes performed optimally at retention times in the range of 4-6 days for thermophilic reactors and 10-15 days for mesophilic reactors.

2.4 Analysis

In the daily operation of TPAD system, effluent pH from each reactor and biogas production was recorded. The composition of biogas was analyzed twice weekly. After the reactors had attained a quasi-steady state (assumed after 3 volume turnovers and less than 5% variation in biogas production during three days operation), the digested sludge was analyzed for Total Solids (TS), Volatile Solids (VS), Volatile Fatty Acids (VFA), alkalinity, ammonia nitrogen and Total Kjeldahl Nitrogen (TKN). Methane production and effluent characteristics were monitored till consistent results were obtained.

An electronic pH meter (Cole-Parmer model 05669-20), calibrated at 25 ^{o}C with standard pH buffers of 4.0, 7.0, and 10.0, was used for pH measurements. Measurements of TS, VS, VFA, alkalinity, total phosphorus and TKN were made twice weekly following the procedures listed in Standard Methods for the Examination of Water and Wastewater [1]. The biogas composition was analyzed using a Gow Mac gas chromatograph equipped with a thermal conductivity detector. The operational temperatures of the injection port, oven and the detector were 150, 50, and 100 ^{o}C, respectively. Gas detection tubes with a LP-1200 pump (RAE systems Inc., Sunnyvale, CA) were used for detection of hydrogen sulfide and ammonia in the biogas. An ammonia electrode (Mettler-Toledo, type 15 230 3000) was used for ammonia nitrogen measurements. Samples were cooled and shipped overnight to certified contract laboratories (University of Iowa, Iowa City, IA) for pathogen analysis.

3. Results and Discussion

To determine the extent of anaerobic biodegradation of dairy cattle manure at varying loads, the TPAD system was subjected to six different TS concentrations referred to as Runs 1-6. Corresponding to the TS concentrations, the organic loading rate to the system varied from 1.87 to 7.70 g VS/L/d. The average feed compositions to the reactor are summarized in Table 2.

3.1 Solids Reduction

Table 3 sums up the system performance with respect to solids reduction for the different Runs. The performance dropped significantly as the total solids concentration was increased to 14.54% (7.70 g VS/L/d). Operational problems were also encountered due to foaming of the thermophilic reactor during Run 6.

Table 2. Average feed characteristics

Characteristics	**RUN 1**	**RUN 2**	**RUN 3**	**RUN 4**	**RUN 5**	**RUN 6**
TS (%)	3.46	5.23	8.17	10.35	12.20	14.54
VS (%)	2.62	3.97	6.30	8.15	9.42	10.78
pH	7.10	7.20	7.10	6.95	6.85	6.70
VFA (mg/L acetate)	2,070 ± 220	3,410 ± 300	6,250 ± 270	9,300 ± 200	10,250 ± 260	12,700 ± 310
Alkalinity (mg/L $CaCO_3$)	3,070 ± 250	4,640 ± 170	8,500 ± 220	7,000 ± 270	7,800 ± 210	9,300 ± 190
TKN (mg/L N)	740 ± 110	1,040 ± 160	1,700 ± 90	2,100 ± 200	2,950 ± 280	3,800 ± 240
NH_3-N (mg/L N)	160 ± 50	220 ± 70	340 ± 60	450 ± 50	770 ± 90	1,230 ± 70
T - Phosphorus (mg/L P)	--	--	695 ± 30	905 ± 18	1,520 ± 70	1,945 ± 65

Table 3. System performance at different runs

Run	**System TS Loading** (g TS/L/d)	**System VS Loading** (g VS/L/d)	**System Performance**	
			TS Reduction (%)	**VS Reduction** (%)
1	2.47	1.87	39.4 ± 1.6	39.7 ± 2.0
2	3.74	2.84	39.1 ± 1.1	39.2 ± 1.4
3	5.84	4.50	40.2 ± 1.3	40.0 ± 1.6
4	7.39	5.82	40.7 ± 0.6	41.5 ± 1.1
5	8.71	6.73	35.6 ± 0.8	37.0 ± 0.7
6	10.39	7.70	28.0 ± 0.7	29.3 ± 1.3

Figure 2 illustrates VS removals achieved by each individual reactor and by the system at the TS concentrations studied. It is evident that the system performance is heavily dependent on the performance of the thermophilic reactor, while the mesophilic reactor improves the effluent quality by consistently achieving additional 12-17% VS reduction. The maximum VS removal of 42.6% was achieved at a TS concentration of 10.35% (5.82 g VS/L/d), determined as the optimum loading for the system.

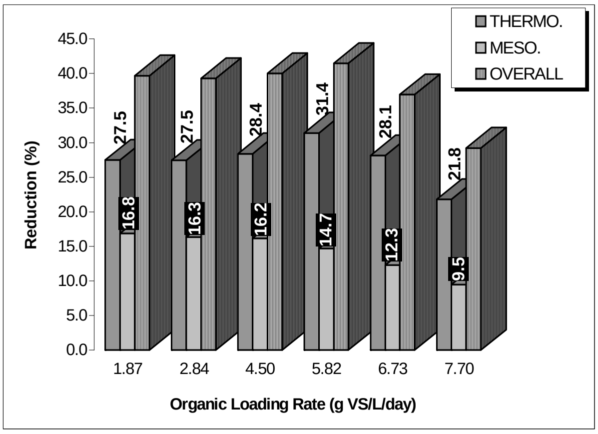


Figure 2. Individual reactor and system volatile solids removal at different organic loadings

3.2 Pathogen Destruction

Effluent quality data from the TPAD system, presented in Table 4, shows the counts of indicator organisms in the thermophilic and mesophilic effluents to be much lower than the limits specified by U. S. EPA for class A designation. The high pathogen destruction achieved could be attributed to the combined effect of high operating temperatures and high volatile fatty acid concentrations in the thermophilic reactor [7].

Table 4. Reduction of indicator organisms in the system

Run	**Fecal Coliforms** (MPN/g TS)			**Salmonella sp.** (MPN/4g TS)		
	Raw Waste	**Thermo.**	**Meso.**	**Raw Waste**	**Thermo.**	**Meso.**
1	1.1×10^5	<1	<1	--	<2	<2
2	1.0×10^6	<1	<1	1000	<2	<2
3	9.3×10^6	<1	<1	1150	<2	<2
4	1.0×10^7	<1	<1	1500	<2	<2
5	1.2×10^7	<25	<25	970	<2	<2
6	2.0×10^8	<25	<25	1300	<2	<2

All samples were tested in triplicate

It is critical to determine the fate of bacterial pathogens in the animal wastes during anaerobic digestion especially when there is a possibility of spread of infectious diseases during land application of the digested slurry. To meet class A standards, 40 CFR Part 503 Regulations require fecal coliform densities in the residual solids from anaerobic sludge digestion systems to be less than 1000 MPN/g of TS and the Salmonella *sp*. densities to be less than 3 MPN/4g of TS [12,13]. The TPAD process met and exceeded the criteria for Class A biosolids at all TS concentrations.

3.3 Methane Recovery

From Table 5, the biogas production from the individual reactors was highest for Run 4. The biogas from the thermophilic and mesophilic reactors contained 58-62% by volume of methane with carbon dioxide being the other major constituent. Methane production rates from the thermophilic stage were higher than the mesophilic reactor in concordance with the higher VS destruction achieved in the thermophilic reactor. The methane recovery from the wastes calculated with respect to VS fed ranged from 0.21-0.22 L CH_4/g VS fed for Runs 1 through 4 (Figure 3). In comparison to the thermophilic reactor, the mesophilic reactor produced greater quantity of methane per gram of VS destroyed at all organic loadings. This suggests that the thermophilic reactor was not efficient in converting all the intermediate products to methane. However, the second-stage mesophilic reactor readily consumed these intermediates ensuring high effluent quality. Beyond the optimal loading of 5.82 g VS/L/d, there was a drop in the biogas production and methane recovery. This suggested that the system would be overloaded if operated at organic loadings in excess of 5.82 g VS/L/d.

Table 5. Biogas volume and composition at different runs

Run	Thermophilic Reactor				Mesophilic Reactor			
	Volume (L)	Composition			Volume (L)	Composition		
		CH_4(%)	H_2S(ppm)	NH_3(ppm)		CH_4(%)	H_2S(ppm)	NH_3(ppm)
1	18.2 ±1.3	59	500	--	12.7 ±0.8	60	150	--
2	29.4 ±1.9	60	500	--	18.2 ±1.5	60	125	--
3	47.1 ±2.4	59	700	10	26.1 ±0.9	60	300	15
4	54.2 ±1.1	61	1000	20	30.0 ±1.7	62	400	20
5	45.1 ±2.1	58	1200	25	21.3 ±1.0	59	550	25
6	26.4 ±2.5	58	1300	25	14.8 ±1.3	59	700	25

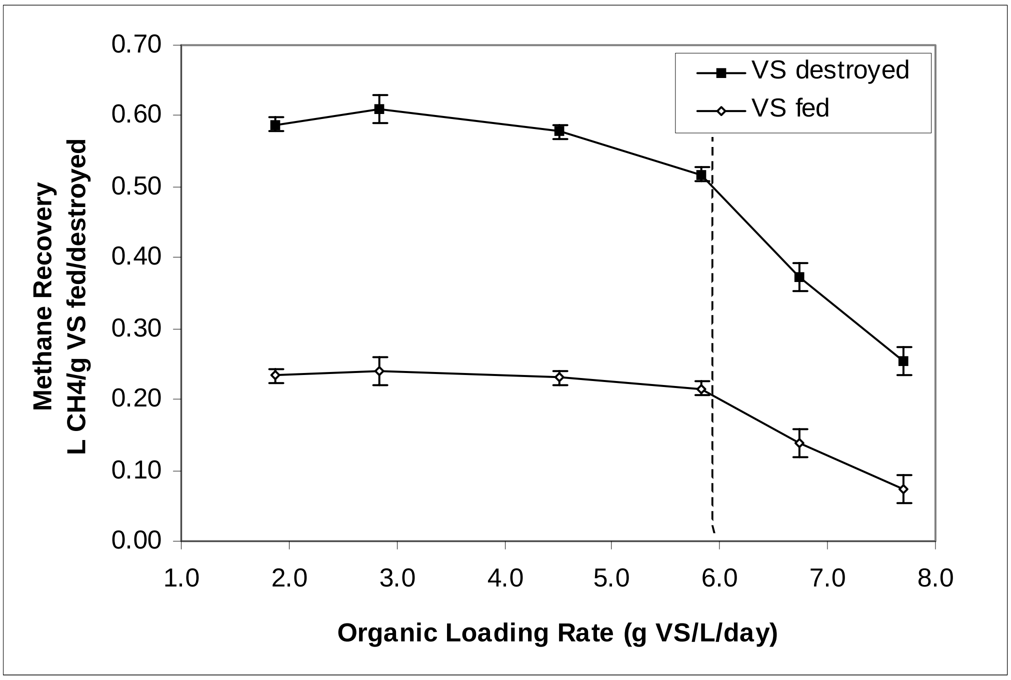


Figure 3. Methane recovery at different organic loadings

3.4 Nutrient Transformation

One of the possible threats to successful operation of TPAD system is the relatively high nitrogen content in cattle wastes. Ammonia-nitrogen concentrations in the range of 1,500 to 3,000 mg/L have been reported to be inhibitory to anaerobic digestion in the mesophilic temperature range [8]. One of the current studies at Iowa State University Environmental Laboratory [11] has reported ammonia-nitrogen concentrations in the range of 4,000 mg/L as inhibitory to anaerobic digestion at thermophilic temperatures.

In this study, the mesophilic reactor was operating at higher ammonia-nitrogen concentrations as compared to the thermophilic reactor due to the conversion of organic nitrogen to ammonia in the mesophilic reactor (Table 6). For Runs 5 and 6, the ammonia-nitrogen concentrations in the mesophilic reactor were close to the inhibitory levels. The drop in performance of the mesophilic system at higher organic loadings could be partially attributed to ammonia inhibition. The variations observed in the total nitrogen (TKN) and total phosphorus concentrations during the digestion process were not significant (Table 6).

3.5 Phosphorus Removal by Lime

On the request of one of the funding agencies, removal of phosphorus at higher pH values was studied with mesophilic effluent from Runs 3, 4 and 5. The soluble phosphorus was precipitated as complex calcium phosphate by the addition of lime to the mesophilic effluent. According to [9], the reactions between calcium and phosphates can be expressed as

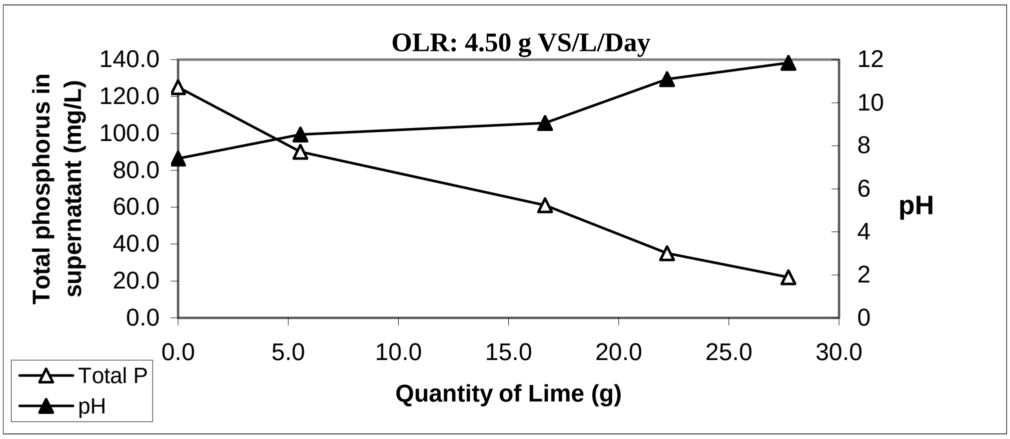
$$Ca^{2+} + (PO_4^{3-}, H_2PO_4^{-}, \text{etc.}) + H^+ \longrightarrow Ca_5(PO_4)_3OH + H_2O$$

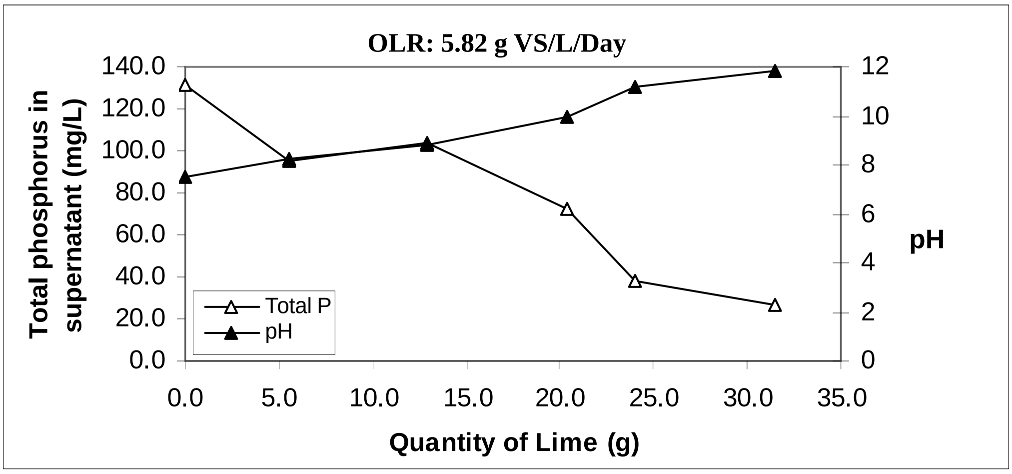
At higher pH (7-12), the calcium phosphates become stable and are not hydrolyzed to release phosphorus into solution.

The mesophilic effluent from runs 3, 4 and 5 contained 913, 1,520 and 1,945 mg/L of phosphorus, respectively. Prior to lime addition, approximately 80-85% of total phosphorus was removed with the biosolids by centrifugation. Analysis of the supernatant after lime addition showed that raising the pH of the effluent to 11 could remove approximately 75% of the remaining phosphorus (Figure 4). Increasing pH above 11 had little effect on further removal of soluble phosphorus.

Table 6. Nitrogen transformation in the system

	TKN and NH_3-N (mg/L N)			
	Thermophilic Effluent		**Mesophilic Effluent**	
	TKN	NH_3-N	TKN	NH_3-N
1	660 ± 170	210 ± 30	640 ± 120	330 ± 40
2	1,000 ± 60	370 ± 80	980 ± 70	500 ± 70
3	1,630 ± 100	660 ± 50	1,600 ± 90	840 ± 60
4	2,000 ± 150	750 ± 70	1,950 ± 100	1,090 ± 60
5	3010 ± 280	1,320 ± 160	2,900 ± 210	1,925 ± 200
6	3,920 ± 290	1,760 ± 190	3,840 ± 260	2,330 ± 190





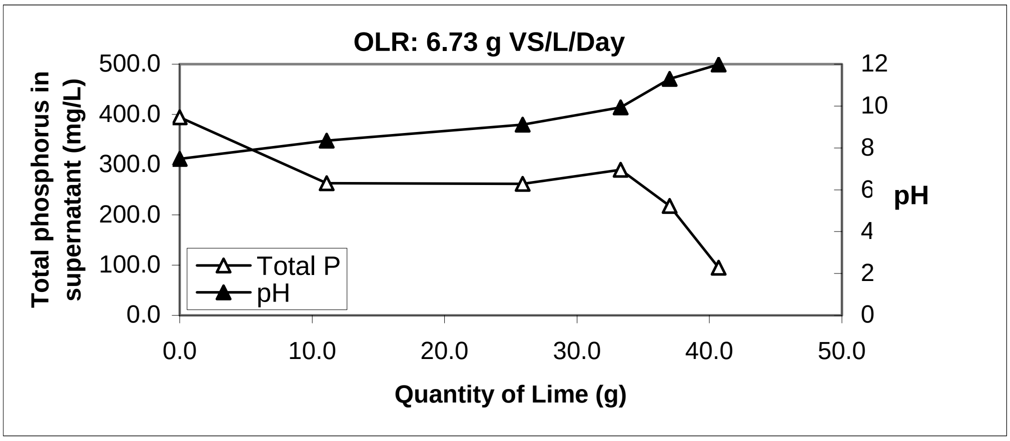


Figure 4. Phosphorus removal by lime

4. Discussion and Conclusions

Anaerobic digestion of cattle wastes using the TPAD technology not only recovers the energy by-product methane, but also provides pathogen-free high nutrient biosolids. The arrangement of two reactors in series, with the thermophilic unit as the first stage followed by the mesophilic unit, can take advantage of both thermophilic and mesophilic conditions. The thermophilic first stage enhances the hydrolysis of some of the recalcitrant organics in cattle wastes that makes it available for acidogenic and methanogenic bacteria in the mesophilic stage. The thermophilic unit operated at a higher temperature and VS loading, achieves higher VS destruction rate. The second mesophilic stage completes the digestion process converting the partially digested organics to methane and carbon dioxide thus fully recovering the energy byproduct from cattle wastes. Conventional mesophilic systems could be modified to two-stage systems by upgrading one of the mesophilic for operation at thermophilic temperatures. In practice, it would also be advisable to place an effluent heat exchanger on the first stage thermophilic digester. This approach could reduce the temperature of thermophilic effluent to the optimum mesophilic level and recover a portion of the energy used in raising the temperature of the incoming waste stream to the thermophilic level. The TPAD process provides sufficient energy to keep the digesters at operating temperature and still provide an additional amount of net energy. However, it would be unwise to associate TPAD technology with generation of electricity alone. The economic value of pathogen-free residual solids and liquid end products has to be identified to make the process economically attractive.

The following conclusions were drawn from the results of this comprehensive study:

1. The TPAD system operated at feed concentrations ranging from 3.46-14.54% TS and a system retention time of 14 days achieved 28-42.6 % reduction in VS. The thermophilic stage accounted for approximately 25-30% of the reduction in volatiles with the mesophilic stage contributing an additional 10-15%.
2. At 14-day retention time, the maximum VS removal of 42.6% was achieved at an organic loading of 5.82 g VS/L/d, which was established as the optimum loading to the system.
3. Nearly 60% of the biogas produced was from the thermophilic stage, consistent with the higher volatile solids destruction in the thermophilic reactor. The methane recovery from the system ranged from 0.54-0.61 L CH_4/g VS destroyed within conditions of optimal loading. The H_2S and NH_3 emissions from the two reactors were less than 1,500 and 25 ppm, respectively.
4. At all organic loadings studied the treated biosolids from the process met Class A pathogen standards specified in 40 CFR Part 503 regulations.
5. Though there was an increase in VFA concentration in the thermophilic reactor, the mesophilic reactor maintained a good effluent quality under optimal loading conditions.
6. The ammonia nitrogen concentrations in the mesophilic reactor were found to be in the inhibitory range for loadings greater than the optimum.

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