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Abstract

Swine production facilities today are larger in size and are concentrated in smaller geographical areas than they were two decades ago. Additionally, there is an increasing trend to base manure land application rates on crop phosphorus requirements rather than crop nitrogen requirements alone. These factors have resulted in a need to find a feasible method for removing phosphorus from swine waste prior to land application. Economically concentrating and transporting excess phosphorus to phosphorus deficient cropping areas would benefit the current production scheme. Forced precipitation of phosphorus as struvite ($MgNH_4PO_4 6H_2O$) is an option for phosphorus concentration and removal. Economic feasibility of phosphorus precipitation improves when reactive phosphorus represents a high percentage of the total phosphorus in slurry, and when a limited amount of chemical amendment is required for the precipitation reaction. In this study, anaerobic digestion of swine slurry increased reactive phosphorus (PO_4^{3-}) and magnesium ion (Mg^{2+}) in solution by 26% and 254%, respectively. Additionally, during phosphorus precipitation experiments, PO_4^{3-} removal and reduction efficiencies were greatest in the tests performed with anaerobically digested swine slurry.

Keywords

Struvite, Phosphorus removal, Swine waste, Anaerobic digestion, Nutrient removal

Disciplines

Agricultural Economics | Agriculture | Animal Sciences | Bioresource and Agricultural Engineering

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L. B. Moody, R. T. Burns, K. J. Stalder

ABSTRACT. *Swine production facilities today are larger in size and are concentrated in smaller geographical areas than they were two decades ago. Additionally, there is an increasing trend to base manure land application rates on crop phosphorus requirements rather than crop nitrogen requirements alone. These factors have resulted in a need to find a feasible method for removing phosphorus from swine waste prior to land application. Economically concentrating and transporting excess phosphorus to phosphorus deficient cropping areas would benefit the current production scheme. Forced precipitation of phosphorus as struvite ($MgNH_4PO_46H_2O$) is an option for phosphorus concentration and removal. Economic feasibility of phosphorus precipitation improves when reactive phosphorus represents a high percentage of the total phosphorus in slurry, and when a limited amount of chemical amendment is required for the precipitation reaction. In this study, anaerobic digestion of swine slurry increased reactive phosphorus (PO_4^{3-}) and magnesium ion (Mg^{2+}) in solution by 26% and 254%, respectively. Additionally, during phosphorus precipitation experiments, PO_4^{3-} removal and reduction efficiencies were greatest in the tests performed with anaerobically digested swine slurry.*

Keywords. Struvite, Phosphorus removal, Swine waste, Anaerobic digestion, Nutrient removal.

In the past, regulations have required that manure application rates be based on nitrogen due to the mobility of nitrate-nitrogen in soil (Sutton et al., 1995). However, as a result of long-term land application practices for field fertilization and livestock waste disposal, elevated levels of phosphorus exist in many U.S. locations (Daniel et al., 1998). This has led to the trend for state regulatory agencies to base their manure management planning requirements on nitrogen and phosphorus in an attempt to balance system inputs and outputs. Switching from an application rate based on crop nitrogen uptake to a rate based on crop phosphorus uptake could increase land area requirements by a factor of 4 to 8 times (Burns et al., 1998). A cost-effective approach to reduce phosphorus levels prior to land application could greatly reduce land requirements for manure disposal.

One approach to removing phosphorus from swine manure prior to land application is the forced precipitation of phosphorus, and its subsequent removal from the waste as a precipitate. A possible phosphorus precipitate is magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$),

commonly called struvite. To form struvite, the ions Mg^{2+}, NH_4^+, and PO_4^{3-} must be available in an alkaline solution (Suzuki et al., 2002) and in a sufficient concentration to provide an adequate precipitation potential (Suzuki et al., 2002; Uludag-Demirer et al., 2007). In wastewater from animal feeding operations, aqueous Mg^{2+} is often the limiting ion. Struvite precipitation can proceed when the product of the ion concentrations exceeds the struvite solubility product. The solubility product is a function of pH; as pH increases the precipitation equilibrium curve for struvite decreases allowing a greater degree of precipitation (Ohlinger et al., 2000).

Forced precipitation of struvite has been pursued in both municipal and agricultural wastewaters. It has been used to reduce phosphorus in wastewaters from both swine and dairy facilities (Nelson et al., 2000; Suzuki et al., 2002; Bowers et al., 2007; Massey et al., 2007). Using a fluidized bed struvite crystallizer Bowers et al. (2007) achieved total phosphorus removal efficiencies as high as 80% in swine lagoon wastewater during a combination of multiple tests, but only as high as 49% in dairy lagoon wastewater. Experiments by Massey et al. (2007) also resulted in low total phosphorus removal rates in dairy lagoon wastewater (14% removal) using a fluidized bed struvite crystallizer process. Susuki et al. (2002) achieved 65% PO_4^{3-} removal on swine wastewater using an aerated crystallization reactor.

During research to prevent the formation of struvite in pipes, Buchanan (1993) hypothesized that availability of Mg^{2+}, NH_4^+, and PO_4^{3-} ions in solution would increase following the microbial digestion of livestock wastes. And in fact, multiple studies show increases in NH_4^+ and PO_4^{3-} following anaerobic digestion (Wrigley et al., 1992; Marti et al., 2008). Additionally, Marti et al. (2008) suggest that magnesium is also released from organic matter as a part of organic matter degradation. Therefore, when anaerobic

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digester pH is not high enough to encourage struvite formation within the digestion vessel, digestion would likely enhance post-digester struvite formation by increasing the reaction limiting ion, aqueous magnesium.

In swine manure slurries it has been shown that a molar ratio of $Mg^{2+}:PO_4^{3-}$ of 1.6:1 (Burns et al., 2003) and a pH of 9.0 (Nelson et al., 2000; Burns et al., 2001) is sufficient to remove greater then 90% of the PO_4^{3-} in solution. The need for a ratio greater then 1:1 in swine slurries supports the hypothesis of Schultz-Rettmer (1991) that high Mg concentrations promote struvite formation by overcoming effects of complexing agents that can bind to Mg.

The objective of this research was to test the hypothesis that anaerobic digestion enhances the availability of Mg^{2+} and PO_4^{3-} ions in solution. And, that increasing the availability of those ions enhances phosphorus precipitation in swine slurry. Several scenarios were tested to optimize the phosphorus precipitation reaction; the variables in our process were pH, magnesium concentration, and method of waste pre-treatment (un-digested or anaerobically digested waste). While the struvite precipitation reaction was the basis for our experiment, the main objective was to determine if anaerobic digestion enhanced phosphorus reductions via precipitation reactions; determining the specific precipitation reaction(s) that occurred in the experiment was not an objective.

MATERIALS AND METHODS

The swine waste used in the study was collected from a shallow pit below a slatted floor farrowing house located at the University of Tennessee Knoxville Experiment Station swine unit. Waste required for the experiment was collected from below the slatted floor using a 1-L dipper. No solids separation was performed on the waste prior to testing. The collected sample was analyzed for reactive phosphorus (PO_4^{3-}), chemical oxygen demand (COD), total solids (TS), volatile solids (VS), soluble magnesium (Mg^{2+}), and ammonium (NH_4^+). In this article, soluble magnesium refers to the aqueous magnesium species, divalent magnesium; i.e. the magnesium that contributes to the hardness of water (APHA et al., 1998). Reactive phosphorus was determined using a Dionex DX-100 ion chromatograph (Dionex Corporation; Sunnyvale, Calif.), COD was measured using a Hach colormetric digestion method (Method 8000, Hach Co., Loveland, Colo.), TS and VS were analyzed using Standard Method 2540C & E (APHA, AWWA, WEF), Mg^{2+} was determined using Hach calmagite colormetric method (Method 8030, Hach Co.; Loveland, Colo.), and NH_4^+ was measured with a Hach test using the Nessler Method (Method 8038, Hach Co., Loveland, Colo.). Following anaerobic digestion and the precipitation reactions, the material was analyzed for PO_4^{3-}, Mg^{2+}, NH_4^+, and TS.

WASTE DIGESTION

Seven liters of material were anaerobically digested in a continuously stirred tank reactor (CSTR); this was considered digested swine slurry. The CSTR consisted of a sealed container (gas outlet line submersed in water to maintain anaerobic conditions) mixed at 140 rpm on a stir plate within an environmental chamber held at 40°C. The swine waste was digested for 36 d. After 36 d, 34% of the initial COD (36,000 mg/L) and 12% of the initial VS (14,300 mg/L) was removed. Phosphorus precipitation reactions were performed with the anaerobically digested slurry at the end of the 36-d digestion period.

Seven liters of material were used for the phosphorus precipitation reactions on undigested swine slurry; these tests were performed upon return from the collection process at the swine unit. Precipitation reactions on the undigested slurry were performed immediately to preserve the integrity of the material.

PHOSPHORUS PRECIPITATION REACTIONS

The reaction scenarios were performed in triplicate in 0.5-L glass beakers. Each of the reactions was performed in a randomized order determined by a random number table (Ott, 1992). Efforts were made during the tests to maintain the consistency of the slurry by stirring the material throughout the process, and thus prevent settling of solids. A list of the reactions and controls used in the experiments is shown in table 1. For each test, slurry was poured from a mixed 20-L carboy into a 1-L beaker. It was stirred in the 1-L beaker for 5 min. While mixing, 0.3 L of material was measured into a graduated cylinder and poured into a 0.5-L glass beaker for the test.

The characteristics of the initial undigested and digested swine slurry are provided in table 2. For clarity, the molar ratios have been reported relative to PO_4^{3-} to show the relative increase in Mg^{2+} resulting from MgO additions. In the un-digested swine slurry, the molar ratio of available ions in solution was 0.27:13.6:1 ($Mg^{2+}:NH_4^+:PO_4^{3-}$); in the digested swine slurry, the ratio of available ions in solution was 0.78:7.8:1 ($Mg^{2+}:NH_4^+:PO_4^{3-}$). In both slurries, Mg^{2+} is the limiting ion. Magnesium was added for the precipitation reactions to obtain $Mg^{2+}:PO_4^{3-}$ ratios of 1.9:1 and 3.2:1. For each test, magnesium oxide (MgO) was added to the 0.3-L sample to increase the magnesium concentration and the pH. Magnesium treatment levels were 0.25 or 0.50 g of added MgO (equal to 0.15 and 0.3 g Mg, respectively). After the addition of MgO, the slurry was placed on a stir plate and mixed until a stable pH measurement was recorded. As the MgO was added, not all of the compound went into solution due to the low solubility of the chemical. For tests with NaOH addition, the NaOH was added until the pH of the material being tested reached 9.0. Tests were performed at either the pH achieved by MgO addition or at a pH of 9.0 (identified in literature as being optimal for the struvite reaction). Finally, the temperature was increased to 35°C. Upon reaching the reaction temperature, mixing continued for a 15-min reaction period. After the reaction, the contents were allowed to settle

Table 1. List of reactions and controls used for phosphorus precipitation reactions.

Undigested Swine Slurry	Digested Swine Slurry
Initial, control (prior to mixing and amendments)	Initial, Control (prior to mixing and amendments)
Stirred and settled, control	Stirred and settled, control
Heated, stirred, and settled, control	Heated, stirred, and settled, control
0.5 g MgO / NaOH to pH of 9	0.5 g MgO / NaOH to pH of 9
0.5 g MgO / No NaOH	0.5 g MgO / No NaOH
0.25 g MgO / NaOH to pH of 9	0.25 g MgO / NaOH to pH of 9
0.25 g MgO / No NaOH	0.25 g MgO / No NaOH

Table 2. Characteristics of the initial undigested and digested swine slurry prior to amendment and precipitation reactions.

	Undigested		Digested	
	Average	Standard Deviation	Average	Standard Deviation
PO_4^{3-} (mg/L)	1256.2	135	1591.2	380
Mg^{2+} (mg/L)	88.3	8	313.3	12
NH_4^+ (mg/L)	3240.0	352	2360.0	178
TS (mg/L)	25120	3051	21417	106

for 15 min. The supernatant was collected off the top of the sample for analysis.

ANALYSIS

After performing the precipitation reactions, collected samples were stored overnight at 4°C. Each sample was analyzed for PO_4^{3-}, Mg^{2+}, NH_4^+, and TS. Triplicate analyses were performed for PO_4^{3-} on each sample. The results of the triplicate analyses for PO_4^{3-} were averaged for statistical analysis. PROC MIXED was used to implement a fixed model for data analysis (SAS Institute, 1996). Fixed effects included in the model were: type of manure (un-digested or digested), level of MgO addition (0.25 or 0.50 g), and NaOH addition (No NaOH addition, NaOH addition until pH of 9 was reached). Orthogonal comparisons were made to determine treatment mean differences. Statistically significant differences were declared at the $\alpha \le 0.05$ level and highly significant statistical differences at $\alpha \le 0.01$.

Positive determination of phosphorus precipitates requires the use of x-ray diffraction techniques. Because the main objective was to determine if anaerobic digestion enhanced phosphorus reductions via precipitation reactions rather than to determine the exact composition of the precipitate, this method was not employed in these experiments to positively confirm the identity of the formed precipitates.

RESULTS AND DISCUSSION
RESULTS OF STATISTICAL ANALYSIS
Anaerobic Digestion Effects on Swine Slurry Characteristics

The least squares means of the slurry characteristics for the undigested and anaerobically digested waste were compared (table 3). Anaerobic digestion increased the amount of magnesium ion in solution; the digested slurry had a mean soluble Mg^{2+} concentration 254% greater than the undigested slurry. This difference was found to be highly significant, supporting the hypothesis that anaerobic microbial digestion aids in releasing bound nutrients to an

available form. While the digested slurry did have an increased PO_4^{3-} concentration, 26% greater than the un-digested waste, the observed difference was not statistically significant. However, the increased PO_4^{3-} concentration does support the idea that anaerobic digestion increased phosphorus ion availability. The difference between the undigested and digested mean NH_4 concentration was statistically significant (27% decrease in NH_4 concentration in the digested waste). This result indicated that NH_3 volatilization occurred in the digested material. A decrease in ammonia as a result of anaerobic digestion was expected; the digester was heated and stirred. Studies have shown that NH_3 volatilization in swine manure is affected by temperature, slurry composition, pH, and water content (Brunke et al., 1988; Sullivan et al., 2003); and, it has been observed that higher ammonical nitrogen concentrations result in high volatilization rates (Brunke et al., 1988). Organic nitrogen content was not determined, and due to the losses via volatilization the conversion of total nitrogen to ammonical nitrogen during the anaerobic digestion process was not defined. Also, as expected, the digested slurry resulted in a lower TS concentration, but the observed difference was not statistically significant.

In the un-digested swine slurry, the molar ratio of available ions in solution was 0.27:13.6:1 (Mg^{2+}:NH_4^+:PO_4^{3-}); in the digested swine slurry, the ratio of available ions in solution was 0.78:7.8:1 (Mg^{2+}:NH_4^+:PO_4^{3-}). The ratios of available ions indicate that the amount of Mg^{2+} amendment necessary to precipitate all of the available phosphate as struvite is considerably less for the digested swine slurry. Additionally, the digested waste offers the potential to remove a larger mass of phosphorus than the un-digested waste because the digested waste has a greater mass of phosphorus ion available in solution (1,591 vs. 1,256 mg on a 1-L basis).

Post-Reaction Results

For the phosphorus precipitation reactions, Mg^{2+} was amended to the reaction volume at 0.25 and 0.5 g MgO per 0.3-L swine slurry. Based on the characteristics of the undigested and digested slurry, the resulting molar ratios of Mg^{2+}:NH_4^+:PO_4^{3-} were as follows: undigested, 0.25 g MgO, 1.9:13.6:1; undigested, 0.5 g MgO, 3.4:13.6:1; digested, 0.25 MgO, 2:7.8:1; digested 0.5 MgO, 3.2:7.8:1. Because the available Mg^{2+} and PO_4^{3-} ions increased with digestion, the ratios of Mg^{2+}: PO_4^{3-} were similar for both the undigested and digested slurry at each Mg amendment level.

Table 4 shows results comparing the effect of the phosphorus precipitation reactions using undigested and anaerobically digested slurry. The PO_4^{3-} concentration was 61% lower ($p < 0.01$) in the reacted digested material as

Table 3. Least squares means (±SE) for pre-reaction PO_4^{3-}, Mg^{2+}, NH_4^+, and TS concentrations for undigested and anaerobically digested swine manure.

	Least Squares Means		Difference Between Means	Standard Error of the Means	Significance[a]
	Undigested	Digested			
PO_4^{3-} (mg/L)	1256.2	1591.2	-335.0	190.36	0.1533 NS
Mg^{2+} (mg/L)	88.3	313.3	-225.0	8.0	<0.0001 **
NH_4^+ (mg/L)	3240.0	2360.0	880	227.5	0.0180 *
TS (mg/L)	25120	21417	3703.3	1762.7	0.1035 NS

[a] (NS) not significant, (*) significant $\alpha \le 0.05$, (**) highly significant $\alpha \le 0.01$.

Table 4. Least squares means (±SE) for post-reaction PO_4^{3-}, Mg^{2+}, and NH_4^+ concentrations for undigested and anaerobically digested swine manure.

	Least Squares Means		Difference Between Means	Standard Error of the Means	Significance[a]
	Undigested	Digested			
PO_4^{3-} (mg/L)	120.5	46.5	74.0	11.9	<0.0001 **
Mg^{2+} (mg/L)	227.4	225.0	2.4	66.1	0.9712 NS
NH_4^+ (mg/L)	2250.8	2206.7	44.2	102.7	0.6363 NS

[a] (NS) not significant, (*) significant $\alpha \leq 0.05$, (**) highly significant $\alpha \leq 0.01$.

compared to the reacted undigested material (table 2). However, there was no observed statistically significant difference in Mg^{2+} or NH_4^+ concentrations between the reacted undigested and reacted digested slurry following the precipitation reactions. Note that for the undigested slurry, the Mg^{2+} concentration was higher then the initial concentration shown in table 3 and that the digested slurry Mg^{2+} was only slightly reduced. This is because reactions included the addition of either 0.25 or 0.5 g MgO.

Equimolar parts of PO_4^{3-}, Mg^{2+}, and NH_4^+ are required to form struvite. However, while not statistically different, a reduction of Mg^{2+} and NH_4^{3-} concentration did occur during the precipitation reactions, and a significant decrease in PO_4^{3-} did take place. Reductions in PO_4^{3-} may still have been the result of struvite formation. The fact that no statistically significant reduction in NH_4^+ or Mg^{2+} occurred may be explained by the fact that while equimolar concentrations of each nutrient are required to form struvite, stoichiometrically far more PO_4^{3-} than NH_4^+ or Mg^{2+} is required on a mass basis (5.3 and 4.0 times more by weight, respectively). This, coupled with the fact that the waste stream had a much higher pre-reaction NH_4^+ concentration than PO_4^{3-} concentration explains the non-significant reduction in NH_4^+ during PO_4^{3-} removal as a precipitant. And, while Mg^{2+} was removed during the reaction, the addition of MgO reduces the amount shown to be removed. When you account for the Mg^{2+} in the pre-reaction sample and the amount of Mg^{2+} added as MgO, the actual amount removed during the reactions ranged between 86.7 and 676 mg/L of volume for both the digested and undigested treatments.

Table 5 shows the SAS results from testing the effect of two MgO treatments, 0.25- and 0.50-g additions. Based on the undigested swine slurry, 0.25-g MgO addition was calculated to provide a stoichiometrically sufficient amount of Mg to form enough struvite to remove all of the PO_4^{3-} in the material. The 0.50-g addition of MgO was also tested to determine if Mg additions above the calculated stoichiometric needs would provide enhanced PO_4^{3-} removal. It was thought that some of the supplemented Mg^{2+} could bind with other compounds and would become unavailable to the precipitation reaction. When comparing the addition of 0.50 and 0.25 g MgO, the difference in the post-reaction concentration of PO_4^{3-} was statistically significant with the 0.50-g MgO treatment providing greater

PO_4^{3-} removal. As expected, the Mg^{2+} concentration following the 0.50-g MgO addition reactions was significantly higher when compared to the concentration following the 0.25-g MgO addition reactions. Concentrations of NH_4^+ following both levels of MgO addition were not significantly different. The results in table 5 show that the resulting PO_4^{3-} concentration from the 0.5-g MgO addition was significantly different then the 0.25-g MgO addition; this shows that MgO addition rate significantly enhanced PO_4^{3-} removal.

The addition or non-addition of NaOH resulted in no observed significant difference between post-reaction PO_4^{3-} and Mg^{2+}. The pH in the phosphorus precipitation reactions utilizing MgO additions ranged from 8.3 to 8.8 depending on which MgO treatment was being evaluated. A pH of 9 to 9.5 is considered to be optimum for struvite formation (Salutsky et al., 1970). For the NaOH treatment tests, NaOH was added until a pH of 9 was reached in the reaction solutions. The purpose of the NaOH treatment was to determine if improved PO_4^{3-} removal in the 0.50-g MgO treatment as compared to the 0.25-g MgO treatment was the result of increased Mg^{2+} concentrations or of increased pH in the 0.50-g MgO treatment level tests. The results shown in table 6 indicate that the pH increase gained from the addition of NaOH did not enhance PO_4^{3-} removal. However, a significant difference in NH_4^{3-} concentrations occurred with or without the addition of NaOH. The increased pH associated with the NaOH treatment may explain the significantly lower NH_4^+ concentrations, caused by the volatilization of NH_3, while PO_4^{3-} and Mg^{2+} concentrations were unchanged by this treatment. The vapor pressure of NH_3 would be expected to increase due to the conversion of NH_4^+ to NH_3 with increased pH. The Henry's Law constant, in mole fraction form, for ammonia gas in water increases five fold from a pH of 8 to 9 at 38°C (Thibodeaux, 1979). This provides one possible explanation for the significant decrease in NH_3 with no increase in phosphate removal.

PHOSPHORUS REDUCTIONS

Table 7 shows the removal of PO_4^{3-} under all of the reaction scenarios. In the phosphorus precipitation reactions, phosphorus removals of greater than 90% were achieved in all but one case following the addition of MgO. Across all tests, reactions in the undigested slurry were not as effective

Table 5. Least squares means (±SE) for post-reaction PO_4^{3-}, Mg^{2+}, and NH_4^+ concentrations in swine manure as affected by MgO addition.

	Least Squares Means		Difference Between Means	Standard Error of the Means	Significance[a]
	O.5 g MgO	O.25 g MgO			
PO_4^{3-} (mg/L)	70.1	96.8	-26.7	10.7	0.0219 *
Mg^{2+} (mg/L)	305	147.4	157.6	66.1	0.0278 *
NH_4^+ (mg/L)	2151.7	2305.8	-154.2	130	0.1092 NS

[a] (NS) not significant, (*) significant $\alpha \leq 0.05$, (**) highly significant $\alpha \leq 0.01$.

Table 6. Least squares means (±SE) for post-reaction PO$_4^{3-}$, Mg^{2+}, and NH$_4^+$ concentrations in swine manure as affected by two treatment levels of NaOH addition (NaOH addition and no NaOH addition)

	Least Squares Means		Difference Between Means	Standard Error of the Means	Significance[a]
	NaOH	No NaOH			
PO$_4^{3-}$ (mg/L)	89.3	77.6	11.7	15.1	0.2855 NS
Mg^{2+} (mg/L)	247.5	204.9	42.6	66.1	0.5273 NS
NH$_4^+$ (mg/L)	2125	2332.5	-207.5	91.9	0.0359 *

[a] (NS) not significant, (*) significant $\alpha \leq 0.05$, (**) highly significant $\alpha \leq 0.01$.

at removing PO$_4^{3-}$ as reactions in the digested swine slurry. Pre-reaction swine slurry concentrations indicted that Mg^{2+} in the digested materials was much greater than in the undigested materials. And, while the pre-reaction PO$_4^{3-}$ concentration of the digested waste was higher than the undigested waste, the difference was not statistically significant. Additionally, statistical analysis of NaOH addition indicated that increasing the pH did not significantly effect the resulting PO$_4^{3-}$ concentration. Therefore, the authors concluded that of the factors analyzed, the increase in Mg^{2+} concentration following anaerobic digestion was most likely responsible for the increased reductions in PO$_4^{3-}$. It should be noted that settling alone removed 28% and 45% of the measured PO$_4^{3-}$ in the undigested and digested slurry, respectively.

CONCLUSIONS

To enhance forced precipitation of phosphorus and reduce chemical amendment requirements for maximum phosphorus reduction, pre-treatment of the swine slurry through anaerobic digestion is beneficial. Anaerobic digestion increased the amount of available reactive phosphorus (PO$_4^{3-}$) by 26% and greatly increased the amount of available magnesium (Mg^{2+}) by 254%. Increasing the PO$_4^{3-}$ concentration means more of the total phosphorus in the slurry is available for removal from solution, and increasing the solution Mg^{2+} means less amendment to meet the stochiometric requirement.

Table 7. Mean PO$_4^{3-}$ concentrations and percent PO$_4^{3-}$ reductions in swine waste resulting from the phosphorus precipitation reactions.

	Mean Resulting [PO$_4^{3-}$] (mg/L)	PO$_4^{3-}$ Removal (%)
Undigested		
Initial	1256.2	N/A
Stirred and settled	900.7	28
Heated, stirred, and settled	734.2	42
0.5 g MgO / NaOH	127.7	90
0.5 g MgO / No NaOH	97.9	92
0.25 g MgO / NaOH	151.1	88
0.25 g MgO / No NaOH	105.1	92
Digested		
Initial	1591.2	N/A
Stirred and settled	872.4	45
Heated, stirred, and settled	868.2	45
0.5 g MgO / NaOH	27.9	98
0.5 g MgO / No NaOH	26.9	98
0.25 g MgO / NaOH	50.5	97
0.25 g MgO / No NaOH	80.5	95

Anaerobic digestion of swine slurry prior to the phosphorus precipitation reactions enhanced PO$_4^{3-}$ removal. Following the addition of MgO, the reacted slurry pretreated with anaerobic digestion resulted in an average of 36% more phosphorus removal; the digested slurry resulted in an average of 1,544 mg removed per L, and the undigested slurry only resulted in 1,135 mg removed per L. Doubling the quantity of Mg amendment produced the greatest reduction in PO$_4^{3-}$ for both the undigested and digested slurries, but that also doubles the Mg input cost. Future work to consider this process for a pilot- or full-scale application should include confirmation of the composition of the precipitate and an evaluation of the value of the precipitate as a fertilizer to provide a more accurate assessment of a full-scale application.

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