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Correlation Equations to Predict the Solids and Plant Nutrient Removal Efficiencies for Gravity Settling of Swine Manure

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ABSTRACT

Experiments were performed to determine the amount of TS, TSS, VS, VSS, COD, TKN, organic-N, total-P, organic-P, and total- K that can be removed from liquid swine manure by settling for 60 minutes. The experiments were conducted using manure samples taken from buildings on three different swine farms. All experiments were replicated 3 times. The swine farms included two pit-recharge manure-handling systems and one flush facility. Significant regression equations were developed from the data that allow the prediction of solids and nutrient content of the influent and effluent manure and removal efficiencies over a TS range of 1730 to 23,850 mg/L. The effects of primary treatment on the ratio of available N to P_2O_5 in the effluent and the impact on the design of further treatment processes will be discussed. These data provide needed information to allow engineers to more precisely design gravity settling structures for primary treatment of swine manure.

Keywords. Manure treatment, Liquid-solid separation, Swine Manure, Manure Management.

INTRODUCTION

Gravity settling has often been used to provide primary treatment for beef and swine feedlot runoff, and flushed dairy manure (Zhang and Westerman, 1997; Chastain et al., 2001; Converse et al., 2000; Lorimore et al., 1995). Most of the studies in the literature provide information on total solids (TS) and volatile solids (VS) removal, and a few provide information on the removal of major plant nutrients (N, P, K). However, none of the studies provide information that can be used to predict the performance of gravity settling over a wide range of influent concentrations that are commonly seen in practice. Furthermore, very little information is available on the performance of gravity settling for primary treatment of liquid swine manure from the flush and pit-recharge facilities common in the Southeastern U.S.

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Bench-scale gravity settling experiments were carried out for manure samples collected from three different swine facilities. The objectives of the study were to: (1) characterize the solids, COD and major plant nutrient concentrations in the swine manure as removed from the buildings, (2) measure the concentrations of solids, COD, and major plant nutrients in the supernatant following 60 min of gravity settling, (3) develop regression equations to predict the supernatant concentrations and the removal efficiencies for the measured constituents, (4) determine if gravity settling improved the degradability of the organic matter (VS, COD), and (5) observe the influence of gravity settling on the available $N:P_2O_5$ ratio in the effluent.

EXPERIMENTAL METHODS

Representative manure samples were collected from swine buildings on three different farms. One farm was a sow farm and included buildings for farrowing, nursery, breeding and gestation. The other two were swine finishing farms.

The sow farm was located at the Starkey Swine Center at Clemson University. Manure was removed from all of the farrowing, nursery, breeding, and gestation barns using an automated flush system. Manure was allowed to collect in a concrete channel below a completely slotted floor. Manure from each building was flushed into a gravity drainpipe that conveyed the flushed manure to a treatment lagoon. Recycled lagoon supernatant was used to flush the manure from the buildings 6 to 12 times a day depending on the building type. Access to the flushed manure in the drainpipe was provided by a manhole that was located between the sow complex and the lagoon. Samples were collected via the manhole during a flush.

The other two farms were swine finishing farms. The buildings on both of these farms were built with fully slotted floors and a pit-recharge manure handling system. The pull plugs and sumps were located outside of the buildings and provided the location for sampling manure. Gravity drainpipes were used to transfer the pit manure to a lagoon. Recycled lagoon supernatant was used to recharge the pits on each farm every 7 to 10 days. One of the farms had two buildings designed to house 600 grow-finish swine. This farm was located in Clarendon County, SC. The other farm had 8 buildings designed to house 880 head of grow-finish swine and was located in Horry County, SC. Finished hogs were produced for two different production companies at the time the manure samples were collected. On one farm, the manure samples were collected from a building with pigs that weighed about 34 kg (75 lb). The average animal weight in the sampled building on the other farm was approximately 68 kg (150 lb).

On-Farm Sampling Procedure

A representative sample of manure was collected while manure was being removed from a building by taking 500-ml samples over time using a long handled sampling cup. For each building, the 500-ml samples were combined in a large plastic container, as they were collected to yield a 15 to 20-L composite sample. This procedure lasted 40 to 60 min for the pit-recharge buildings, and samples were collected at even time intervals as the manure flowed from the building. The duration of a single flush at the sow farm was only 1 to 2 min. Therefore, 500-ml samples were collected continuously for the duration of a flush. This procedure was followed for three different flush events on the sow farm to provide about 15 L of as removed sample. The large composite samples were placed on ice and were transported to the USDA-ARS Coastal Plains Soil, Water, and Plant Research Center where gravity settling experiments and the majority of the solids, COD, and plant nutrient analyses were performed. The composite samples were stored in a large refrigerator prior to the gravity settling experiments.

Gravity Settling Experiments

Gravity settling experiments were conducted with 1 L Imhoff settling cones using the procedures defined by APHA (1995). The steps used in the gravity settling experiments were as follows: (1) a well-mixed sample of the manure removed from a building was collected to define the influent solids, COD, and major plant nutrient concentrations, (2) a well-mixed 1-L influent sample was decanted into an Imhoff settling cone and was allowed to settle for 60 min., and (3) at the end of the settling period the supernatant was decanted and analyzed to define the effluent solids, COD, and plant nutrient concentrations. This procedure was replicated 3 times for each of the three as removed manure samples to provide 9 observations for the influent and effluent.

Quantities Measured and Calculation of Removal Efficiencies

The influent and effluent samples were analyzed to determine the concentrations of the following constituents: total solids (TS), total suspended solids (TSS), volatile solids (VS), volatile suspended solids (VSS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN = NH_4^+-N + NH_3-N), total elemental phosphorous (TP), inorganic-P (Ortho-P), and total elemental potassium (TK). The organic-N (Org-N) was the difference between TKN and TAN. The organic-P was determined as (TP - Ortho-P). The TS and VS were determined for each influent and effluent pair as the average of two subsamples using standard oven drying and furnace incineration techniques (APHA, 1995). The TSS, VSS, and COD were measured using the standard techniques given in APHA (1995). The values reported are the means of two subsamples.

Regression equations were developed from the pooled data set to relate the concentrations of TSS, VS, VSS, COD, and defined plant nutrients to the TS concentration of the as removed, or influent, manure samples. Regression equations were also developed to relate the effluent concentrations of the defined constituents to the corresponding influent concentrations. The removal efficiencies were computed using the prediction equations as:

$$RE_{Cj} = 100 \cdot (C_{i\ IN} - C_{j\ OUT}) / C_{j\ IN}. \quad (1)$$

Where,

RE_{Cj} =	Removal efficiency of the j^{th} constituent,
$C_{i\ IN}$ =	Influent concentration of the j^{th} constituent, and
$C_{j\ OUT}$ =	effluent concentration of the j^{th} constituent.

RESULTS AND DISCUSSION

Constituent Concentrations of the Influent Samples

The concentrations of the solids, COD, and major plant nutrients from all three swine farms were described by the regression equations given in Table 1. The concentrations of TSS, VS, VSS, COD, TP and TK were linearly correlated with the TS concentration. The TAN concentration was best predicted by a correlation with TKN, and Org-P was best correlated with TP. Significant correlations were also found for Org-N and Ortho-P with respect to TS. However, the data are best represented by the equations given in the table. The influent organic-N concentration was computed as (TKN – TAN) and the influent Ortho-P concentration was calculated as (TP – Org-P). The following statistics are also included in the table: coefficient of determination (R^2), standard error of the y-estimate ($S_{y \cdot x}$), standard error of the slope of the regression line, and the range of observed y-values.

Table 1. Regression equations that describe the solids, COD and major plant nutrient concentrations in swine manure as removed from the buildings. Total solids (TS) in the manure ranged from 1730 to 23,850 mg/L and n = 9 for all regression equations.

Regression Equation	R^2	$S_{y \cdot x}$ (mg/L)	Standard Error of the slope	Range of y-values (mg/L)
TSS = 0.832 TS - 1073	0.9939	656	0.025	400 to 18,500
VS = 0.699 TS - 698	0.9910	671	0.025	430 to 15,740
VSS = 0.580 TS - 579	0.9910	557	0.021	360 to 13,060
COD = 0.936 TS - 381	0.9779	1416	0.053	900 to 21,590
TKN = 0.112 TS	0.8899	352	0.008	230 to 3,020
TAN [1]= 0.554 TKN + 29	0.9508	143	0.048	160 to 1,600
TP = 0.052 TS	0.9044	162	0.004	90 to 1,430
Org-P [2] = 0.894 TP - 59	0.9945	37	0.025	20 to 1,240
TK = 0.049 TS + 185	0.8881	176	0.007	160 to 1,340

[1] TAN = (NH_4-N + NH_3-N), Org-N = (TKN – TAN)
[2] Ortho-P = (TP – Org-P)

Regression Equations to Predict the Effluent Solids, COD, and Plant Nutrient Concentrations

All constituent concentrations of the supernatant following 60 min of gravity settling were described by pooled correlations with the influent concentrations given in Table 2. The two equation forms that best described the data were: $y = c x^n$, and $y = b x$ where x is the influent concentration. Only the soluble plant nutrients, TAN, Ortho-P, and TK, were best represented by the equation $y = b x$. The values of R^2 for the soluble plant nutrients ranged from 0.9874 to 0.9994 and the slope of each line was not significantly different from 1.0. Therefore, gravity

Table 2. Regression equations to predict supernatant concentrations of solids, COD, and major plant nutrients following 60 min of settling.

Regression Equation	R^2	Standard Error of n or b [1]	Mean Residual [2] (mg/L)	Standard Deviation of Residuals (mg/L)
$TS_{OUT} = 8.12\ TS_{IN}^{0.71}$	0.9757	0.042	177	952
$TSS_{OUT} = 4.38\ TSS_{IN}^{0.72}$	0.9763	0.043	230	866
$VS_{OUT} = 2.67\ VS_{IN}^{0.81}$	0.9896	0.031	188	729
$VSS_{OUT} = 3.81\ VSS_{IN}^{0.74}$	0.9726	0.047	95	689
$COD_{OUT} = 3.34\ COD_{IN}^{0.81}$	0.9613	0.062	339	2470
$TKN_{OUT} = 1.15\ TKN_{IN}^{0.95}$	0.9926	0.031	1	126
$TAN_{OUT} = 1.00\ TAN_{IN}$	0.9994	0.005	NA [3]	NA
$TP_{OUT} = 7.87\ TP_{IN}^{0.52}$	0.8988	0.066	4	49
$\text{Ortho-P}_{OUT} = 1.00\ \text{Ortho-P}_{IN}$	0.9874	0.017	NA	NA
$TK_{OUT} = 0.98\ TK_{IN}$	0.9915	0.023 [4]	NA	NA

[1] The following equation forms were used to represent the data: $y = c x^n$ and $y = b x$.
[2] Residual = (data – predicted value)
[3] NA = not applicable
[4] Number of observations is 5. Four pairs of data were not available due to insufficient supernatant sample volume.

settling did not remove TAN, Ortho-P, or TK. Only the solids and organic plant nutrients associated with the settled particles were removed.

The effluent concentrations of all other constituents were well predicted by a power law. The values of R^2 ranged from 0.8988 to 0.9926. Since fitting the data to a power law requires the natural log transform of both the x and y-values the variance about the regression line is artificially compressed and $S_{y \cdot x}$ does not realistically reflect the error in the y-estimate in terms of mg/L. Therefore, the residual and standard deviation of the residuals were computed and are given in Table 2 for each power law relationship. The standard deviation of the residuals provides the best estimate of the error in the y-estimate. It is interesting to note that the exponent, n, is not significantly different for TS, TSS and VSS. In addition, the exponents for VS and COD were the same.

Significant power law relationships were also found for Org-N_{OUT} and Org-P_{OUT} (R^2 = 0.8651 and 0.9000). However, the data are best represented by predicting Org-N_{OUT} and Org-P_{OUT} as:

$$\text{Org-N}_{OUT} = (\text{TKN}_{OUT} - \text{TAN}_{OUT}), \text{ and} \tag{2a}$$

$$\text{Org-P}_{OUT} = (\text{TP}_{OUT} - \text{Ortho-P}_{OUT}). \tag{2b}$$

Where,

$$\text{TAN}_{OUT} = \text{TAN}_{IN} \text{ (Table 1), and}$$

$$\text{Org-P}_{OUT} = \text{Org-P}_{IN} \text{ (Table 1).}$$

Removal Efficiencies

Removal efficiencies were computed using equation 1. The influent concentrations were calculated using the equations given in Table 1 and the effluent concentrations were predicted using the equations in Table 2 with equations 2a and 2b. Since only solids, COD, and plant nutrients associated with the settled solids were removed the results were plotted against the influent TS values in Figures 1 and 2.

The removal efficiencies of all of the solids, COD, TKN, Org-N, TP, and Org-P increased in a curvilinear manner as TS_{IN} increased. The greatest removal efficiencies were for organic-P, TSS, and VSS. The removal efficiency for TS ranged from 10 to 56% whereas 23 to 58% of the VS were removed. Less COD was removed than VS in all cases (17 to 50% removal for COD). The lower COD reduction indicates that a greater fraction of the COD was soluble as compared to VS. As a result, it may be better to design secondary anaerobic treatment processes based on COD loading rather than VS loading. It is also important to note that more Org-P was removed than Org-N in all cases. Similarly, more TP was removed than TKN. Significantly higher removal of phosphorous than nitrogen would assist farmers in managing P-based land application requirements.

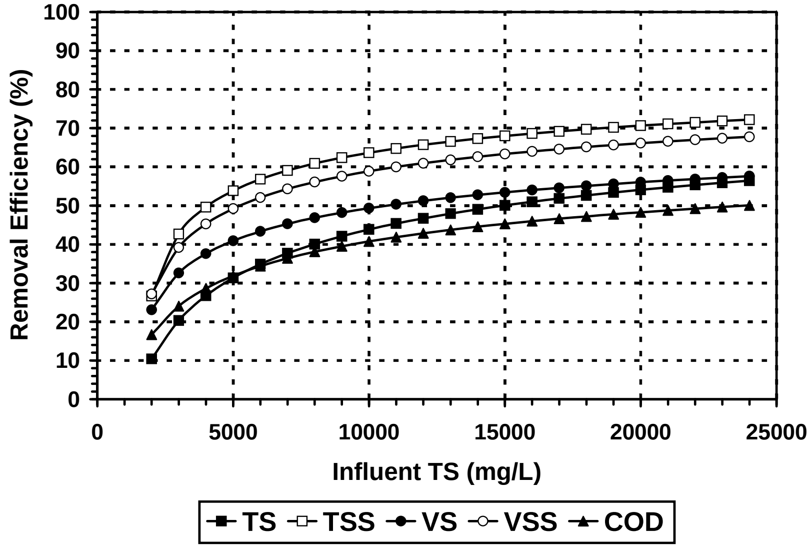

Figure 1. Removal efficiencies for solids and COD following 60 min of gravity settling.

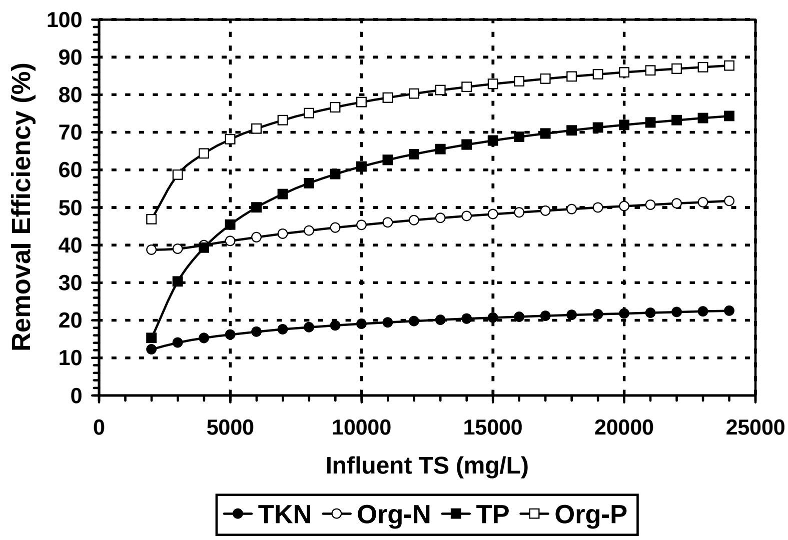

Figure 2. Removal efficiencies for nitrogen and phosphorous following 60 min of gravity settling.

Influence of Gravity Settling on Plant Nutrients and Organic Concentrations

The effluent from a gravity-settling basin can receive additional treatment in a lagoon, anaerobic digester, or be applied to cropland. Liquid-solid separation processes alter the concentrations of plant nutrients, VS and COD. They can also alter the fraction of the total plant nutrients and organic matter that is in the soluble form. Soluble plant nutrients are readily available for uptake by plants. Anaerobic microbes more easily use soluble organic matter for energy.

The influence of gravity settling on the major plant nutrient, VS, and COD composition of the effluent is demonstrated for three cases in Table 3. The results in the table indicate that gravity settling slightly decreased the VS/TS ratio, and increased the fraction of soluble VS (DVS/VS) by a factor of 1.7 to 2.1. Therefore, the effluent VS would be more easily degraded in an anaerobic reactor than the influent. The COD/TS ratio of the effluent was similar to the influent. This is to be expected since a greater fraction of the COD was soluble as indicated by lower removal efficiencies for COD than for VS and VSS. The fraction of the TKN that is soluble was increased significantly by gravity settling (18 to 26 %) and the Ortho-P/TP ratio increased by a factor of 1.8 to 3.6. Therefore, the N and P in the effluent was more plant available that the untreated manure.

The nitrogen in manure that can be readily used by a plant is defined as the available nitrogen (AN). Only a portion of the organic-N in manure will be mineralized during a growing season. The amount of organic-N that is converted to NH_4^+-N depends on a variety of factors. The most important are soil temperature, moisture, and pH. The amount of organic-N that will be mineralized can vary from 30% to 90% depending on soil conditions and manure type (Chastain et al., 2002). Therefore, the mineralization factor, m_F, ranges from 0.3 to 0.9. A portion of the TAN in manure can be lost following application. However, the amount lost is comparable to that lost when applying commercial fertilizers (Montes, 2002). Therefore, the estimate of the AN that should be used to compare animal manure to commercial N sources is:

$$AN = m_F \text{ Org-N} + TAN. \qquad (3)$$

Most agricultural crops do not require equal amounts of N, P_2O_5, and K_2O. Most crops require 2 to 3.6 times more N than P_2O_5 and almost the same amount of K as P (Table 4). Since gravity settling removed more TP than TKN the AN/P_2O_5 ratio of the effluent should be greater than the influent.

Table 3. Influence of gravity settling on plant nutrient and organic matter composition of swine manure.

	Influent TS = 0.5%		Influent TS = 1%		Influent TS = 2%	
Constituent	Influent	Effluent	Influent	Effluent	Influent	Effluent
TS (mg/L)	5,000	3,434	10,000	5,618	20,000	9,189
VS (mg/L)	2,797	1,653	6,292	3,188	13,282	5,839
VS/TS	0.56	0.48	0.63	0.57	0.66	0.64
VSS (mg/L)	2,321	1,179	5,221	2,148	11,021	3,734
DVS/VS	0.17	0.29	0.17	0.33	0.17	0.36
COD (mg/L)	4,299	2,929	8,979	5,319	18,339	9,486
COD/TS	0.86	0.85	0.90	0.95	0.92	1.03
TKN (mg/L)	560	469	1,120	907	2,240	1,752
TAN (mg/L)	339	339	649	649	1,270	1,270
TAN/TKN	0.61	0.72	0.58	0.72	0.57	0.72
TP (mg/L)	260	142	520	203	1,040	292
Ortho-P (mg/L)	87	87	114	114	169	169
Ortho-P/TP	0.33	0.61	0.22	0.56	0.16	0.58
TK (mg/L)	430	430	675	675	1,165	1,165
Mineralization = 0.3						
AN (mg/L)	405	378	790	726	1,561	1,415
AN/TKN	0.72	0.81	0.71	0.80	0.70	0.81
AN/P_2O_5 [1]	0.69	1.17	0.67	1.57	0.66	2.13
AN/K_2O [2]	0.78	0.73	0.97	0.89	1.11	1.01
Mineralization = 0.6						
AN (mg/L)	472	417	932	804	1,852	1,559
AN/TKN	0.84	0.89	0.83	0.89	0.83	0.89
AN/P_2O_5	0.80	1.29	0.79	1.74	0.78	2.35
AN/K_2O	0.91	0.80	1.15	0.99	1.32	1.11
Mineralization = 0.9						
AN (mg/L)	538	456	1,073	881	2,143	1,704
AN/TKN	0.96	0.97	0.96	0.97	0.96	0.97
AN/P_2O_5	0.91	1.41	0.91	1.90	0.91	2.57
AN/K_2O	1.04	0.88	1.32	1.08	1.53	1.21

[1] TP = 0.44 P_2O_5
[2] TK = 0.83 K_2O

Table 4. Nutrient requirements of some common crops (Camberato, 2001, MWPS, 1985).

Crop	Yield	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	N/P_2O_5	N/K_2O
Corn (total plant)	8.7 m^3/ha	149	65	150	2.29	0.99
	13.1 m^3/ha	207	90	241	2.30	0.86
Wheat	4.4 m^3/ha	96	38	113	2.53	0.85
Fescue hay	6700 kg/ha	130	63	178	2.06	0.73
Bermuda hay	13,500 kg/ha	336	94	282	3.57	1.19

1 bu/ac = 0.0871 m^3/ha
1 lb/ac = 1.12 kg/ha
1 ton/ac = 2244 kg/ha

Estimates of the AN, and the AN/TKN, AN/P_2O_5 and AN/K_2O ratios are given in Table 3 for mineralization factors of 0.3, 0.6 and 0.9. In all cases, gravity settling improved N availability, and increased the AN/P_2O_5 ratio. The greatest improvement in the AN/P_2O_5 ratio was for the most concentrated influent concentrations (TS = 1% or 2%). The effluent from gravity settling was a more balanced N and P nutrient source for most common crops than the manure removed from the buildings. The AN/K_2O ratio was reduced, but was still close to the desirable range for most crops (Table 4).

Obviously the organic-P and N removed by settling is in the settled solids. However, the settled solids occupy 25% to 32% of the influent volume (Baker, 2002). Therefore, gravity settling can significantly reduce the volume of high phosphorus manure that may need to be transported to a remote field to be utilized.

CONCLUSIONS

Gravity settling experiments were performed on manure samples removed from swine buildings on three different farms in South Carolina.

- The concentrations of VS, VSS, COD, TKN, TAN, TP, organic-P, and TK in the manure from all three buildings could be well described by a common set of regression equations.
- Gravity settling did not remove any TAN, Ortho-P, or TK.
- The supernatant concentrations from all three farms following 60 min of settling were well described by a common set of power law equations.
- The removal efficiencies for TS, TSS, VS, VSS, COD, TKN, Org-N, TP, and Org-P increased in a curvilinear manner as TS increased from 1,730 to 23,850 mg/L.
- Gravity settling was more effective at removing VS than COD.
- Gravity settling removed more Org-P than Org-N.
- The ratio of soluble VS to VS in the effluent was greater than the influent by a factor of 2. Therefore, the effluent would be more easily degraded in an anaerobic treatment process.
- Gravity settling improved the availability of N and P in the supernatant as compared to the influent.

- The ratio of available N to P_2O_5 was increased favorably to more closely match the needs of common crops.

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