The RE-Cycle System for Hog Waste Management

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ABSTRACT. *The RE-Cycle system is a combination of technologies for improving the environmental sustainability of hog production. The principal components are belt-based manure harvesting and gasification of the solids for recovery of energy and ash. The belt limits emissions of* NH_3 *and* CH_4 *to 1 kg/pig/y. Manure is collected in separate liquid and solid streams. Solids are harvested at 50% DM. The energy content of the solids (19.7 MJ/kg DM) is similar to wood making them suitable for thermochemical processing. A fixed- bed, batch-fed gasifier was chosen for its ease of operation, processing temperature (>800 °C), and ability to accept a wide array of feedstocks. Its only products are a product gas, a sterile mineral ash, and waste heat. Combustion of the product gas eliminates tars and provides heat to sustain the process and generate power.* NO_x *and* SO_2 *emissions are low. Swine waste solids, chicken litter, and chicken, turkey, and pig mortalities have each been processed in this unit. Ash mineral content is dependent upon the composition of the gasifier feedstock, but is generally high in P, K, and Ca. Ash minerals are bioavailable and can be used as a mineral supplement in animal feeds. Feeding trials have demonstrated the bioavailability of its mineral constituents. Mass balance data indicate good nutrient accountability.*

Keywords. *swine housing, animal manure, gasification, waste nutrients, waste management, sustainable agriculture.*

INTRODUCTION

The United States currently imports over 60% of its petroleum supply (EIA, 2004). The push toward energy independence and environmental sustainability has focused attention on biomass since it is renewable, widely available, and, unlike fossil fuels, makes no net contribution to greenhouse gas emissions (Gielen et al, 1998). It has been estimated that biomass could supply 56% of US gasoline needs (Riley, 2001), essentially replacing the imported oil. Animal wastes are a valuable source of bioenergy and offer advantages such as continuous availability without long-term storage, energy content comparable to other traditional sources such as wood, and low intrinsic value due to present disposal costs.

Swine waste solids are 1 to 10 % dry matter (DM) under present harvesting methods (Smith et al., 2000). Attempts to reduce the moisture content have focused on post-collection technologies such as centrifuges, settling basins, and screen separators that generally have low solids recovery, leave a problematic residual aqueous stream, and do not address the barn emissions that are responsible for over 50% of the NH_3 emitted from hog farms (Doorn et al., 2002). Moreover these technologies suffer from high investment costs for equipment, maintenance, and skills on the farm level (Westerman and Bicudo, 2000). In order to capture energy from the solids, they must be sufficiently dry (50 to 70% DM) to permit cost effective transport and processing.

One promising method of capturing the energy of biomass is through gasification. This oxygen-deprived, thermal decomposition technology converts biomass to low molecular weight combustible gases and retains mineral nutrients in a sterile ash byproduct rich in P and Ca. In the reducing atmosphere of the gasifier, N is converted to NH_3 that can be easily scrubbed from the product gas stream. Given the low sulfur content of biomass, SO_x emissions are far less than in coal-fired processes (Graham et al., 1996). The resulting product gas can be combusted to sustain the gasification process and waste heat can be captured to heat buildings, generate steam, or provide power through a Sterling engine. The non-odorous ash by-product can be cost-effectively transported for use as a mineral supplement in animal feeds, as a fertilizer ingredient, or as a building materials component.

The objective of the research presented here was to demonstrate a management strategy that would avoid the negative environmental consequences of hog production while capturing the energy and nutrients of waste in value-added products. The belt-based housing system is designed for separate collection of urine and feces and for improving the air quality in and emissions from hog buildings. The harvested solids have been processed through gasification to dispose of the waste and recover valuable nutrients. Ash digestibility has been evaluated in vitro and in vivo. This approach also allows for energy capture in the form of heat and steam.

EXPERIMENTAL PROCEDURES

The belt-based housing was modeled after a conventional grow-finish facility at 75% of full scale (Figure 1). Pens were two-thirds solid floor, one-third slatted floor (tri-bar, Nooyen, Mt. Sterling, KY).   A high-density polyethylene (1 mm thick) belt conveyor system (Big Dutchman, Vechta, Germany) was installed beneath the tri-bar. There were 5 pens with 16 pigs per pen (25-55 kg) at a stocking density of 0.63 m^2 pig^{-1}. This is similar to the commercial stocking density of 0.4 to 0.7 m^2 pig^{-1} for pigs of 18 to 72 kg body weight (Meyer et al., 1991). The solid flooring had an 8% slope allowing liquids to run off into the belt gutter. The 1º lengthwise slope of the belt, designed to mimic the slope of a commercial building, insured that urine flowed continuously into an enclosed liquid collection vessel at the end of the belt. Two different gutter designs, the “duct” design and the “trough” design, were evaluated for odor and emissions reduction and for ease of cleaning. Animals were fed a standard commercial diet and monitored for weight gain, feed and water intake, and waste production. Ammonia and CH_4 concentrations in the exhaust air from the belt housing facility were determined by Fourier Transform Infrared Spectroscopy (FTIR) as described in van Kempen (2001). Emissions were calculated, after subtraction of background levels in the input air, as the detected differential concentration times the ventilation rate at the time of analysis. The detected differential concentration was multiplied by the ventilation rate at the time of analysis to determine emission levels over time. Materials harvested from the belt were characterized by proximate and ultimate analysis (Hazen Research Laboratories), and mineral composition was determined in house by inductively coupled plasma spectroscopy (ICP). Energy content was established by bomb calorimetry and dry matter determinations were calculated from weights before and after drying samples in a 60 ºC oven till weight change was less than 1% in a 24 h period.

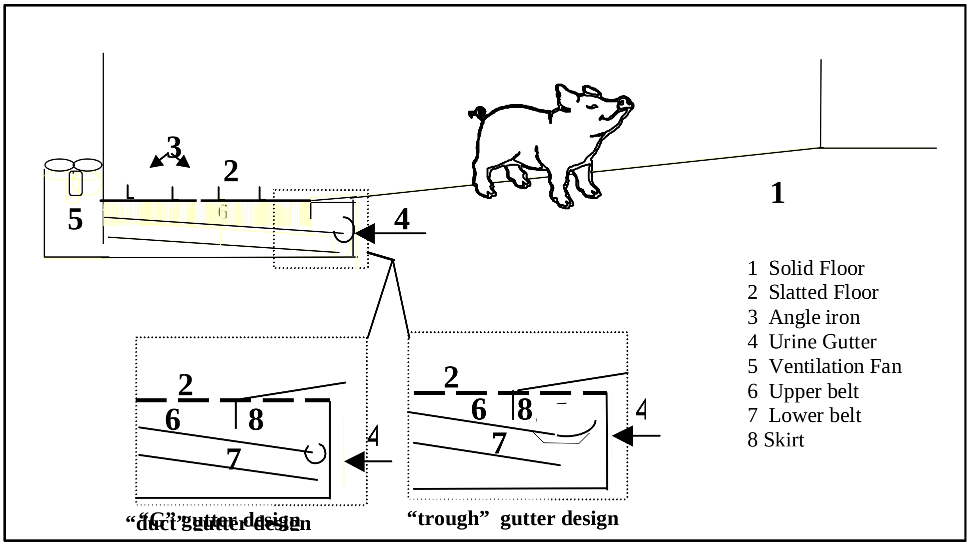

Figure 1. Schematic diagram of the pen and belt layout as tested. The belt is positioned beneath the slats so that animals defecate most on the highest portion of the belt. Urine is allowed to run off into a gutter that continuously carries it out of the room, by gravity flow, into a closed container. The "duct" and "trough" gutter designs are shown in the expanded views of the boxed pen area.

Gasification employs heat and sub-stoichiometric amounts of oxygen to break down, or crack, the feedstock into carbon monoxide and hydrogen gases, as well as other low molecular weight gases. The idealized, general equation (Reed and Gaur, 1999) is:

$$(1) \qquad CH_{1.4}O_{0.6} + 0.35\ O_2 \rightarrow 0.4\ CO + 0.6\ H_2 + 0.4\ CO_2 + 0.1\ H_2O + 0.2\ C$$

For biomass, temperatures are generally held below 1000 ºC to avoid agglomeration within the ash bed. Gasification studies were conducted in a Brookes Gasification Process (BGP) gasifier. This is a batch-fed, indirectly heated, staged-combustion gasifier selected for its simplicity and ease of operation (Figure 2). At start-up, the burner in the secondary chamber combusts propane to heat the firebrick and, indirectly, the primary chamber containing the feedstock. At temperatures of 600 to 900 ºC, biomass feedstock is cracked into low molecular weight gases that are then drawn into the secondary chamber where they are combusted to sustain the process. Ash is removed after completion of the feedstock processing. Combustion gases exit the flue along with waste heat. Gases in the two chambers and the flue are monitored at 15 minute intervals to evaluate temperature, NO_x, SO_2, CO, CO_2, and O_2 levels using a combustion meter (Kane May Instruments). Temperature and oxygen availability can be controlled during the reaction. This control and the static nature of the system result in a clean process that meets both European and Californian emission standards without requiring gas cleanup.

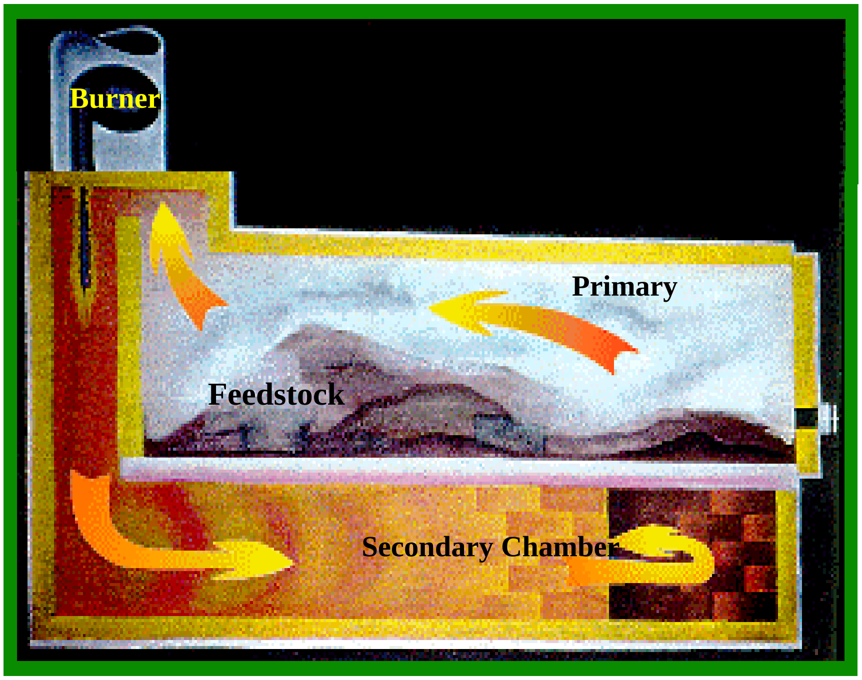

Figure 2. Schematic of the Brookes Gasification Process gasifier. Heat from the burner in the secondary chamber heats the primary chamber containing the feedstock. Gases from the feedstock are drawn into the combustion chamber to sustain the reaction.

RESULTS AND DISCUSSION

BELT OPERATION, PIG PERFORMANCE, AND EXCRETA PROPERTIES

Belt operating variables were evaluated in the first two experiments in order to optimize performance. Prior to data collection, it was hypothesized that the DM content would increase with belt residence time; this was evaluated in Exp. 1. DM content of the recovered solids was found to decrease after 30 h of belt residence time (data not shown). Apparently, when solids remained on the belt for greater than 30 h, the increased fecal load trapped more of the urine thereby reducing the DM content. Collection time-of-day was examined in Exp. 2 by harvesting waste solids at a 27-hour interval with 3 replicates of each time-of-day. A sigmoidal DM pattern was observed (Figure 3). Collections at 06:00 resulted in a 9.8 ± 5.0% DM increase over collections at 15:00. The diurnal activity pattern of the pigs probably produced this result since animals eliminate less at night when they are resting and more when they first eat and become active in the morning. In all subsequent experiments, the belt contents were harvested every 24 hours at 06:00 resulting in an average DM content of 49 ± 4% (TABLE 1). At this DM content, swine feces typically have a brittle, dry appearance externally with a moist core present in larger pieces. It does not clump or pack during handling and it has minimal odor.

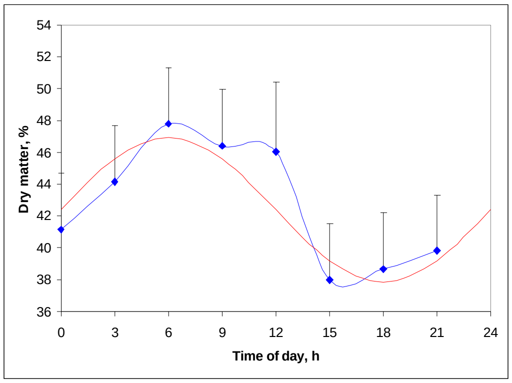

Figure 3. Effect of collection time-of-day on feces DM content. Belt residence time was constant at 27 h and each time-of-day was evaluated in triplicate.

TABLE 1. Experimental parameters and animal performance for five trials designed to evaluate a housing system employing a belt for harvesting urine and feces separately. Data are expressed on a per animal basis, except as indicated.

Trial date and Number	Aug 01	Jan 02	Mar 02	Oct 02	Apr 03	Mar 02	Mean ± SE
	1	2	3	4	5	3	
						Ref.	
N, number of animals	100	80	80	80	80	80	
Avg. T, °C	28	30	26	22	25		26 ± 3
Avg. humidity, %	66	54	52	64	64		60 ± 5
Gutter design	duct	duct	duct	trough	trough	none	
Ave. Wts, in - out, kg	23-57	27-55	23-51	30-57	32-56	24-53	
ADG, kg·d-1	0.79	0.76	0.82	0.97	0.83	0.83	0.83 ± 0.07
ADFI, kg·d-1	1.54	1.52	1.72	1.96	1.73	1.84	1.69 ± 0.16
Gain/Feed	0.51	0.50	0.48a	0.48	0.51	0.45b	0.50 ± 0.02
Fecal output, kg DM·d-1	0.23	0.26	0.22	0.34	0.26	ND	0.26 ± 0.04
Fecal DM as coll'd, %	§	52	54	43	46	ND	49 ± 4
Urine output, L·d-1	ND	1.05	1.54	1.27	1.42	ND	1.32 ± 0.19
NH3 emission, kg·y-1,c	1.08	0.80	0.84	1.20	1.24	ND	1.03 ± 0.18
CH4 emission, kg·y-1	1.27	1.06	0.75	1.39	0.76	ND	1.05 ± 0.26

Collected feces indicate a fecal DM production of 0.26 ± 0.05 kg·pig^{-1}·day^{-1} (Table 1), similar to the 0.27 kg reported by Smith et al. (2000) for the grower pig. Absolute levels of NH_3 emissions averaged 1.0 ± 0.2 kg NH_3·pig^{-1}·y^{-1} over the five experiments (Table 1). This suggests a 73% reduction from the literature value of 3.7 kg NH_3·pig^{-1}·y^{-1} for conventional barns (Doorn et al., 2002). The low levels of NH_3 are attributed to the minimal contact time between urea and the fecal microbes that metabolize it to NH_3 and CO_2 (Rom, 1995) and to the rapid sequestering of the urine in closed containers. Emissions of CH_4, a potent greenhouse gas, were only 1.05 ± 0.26 kg CH_4·pig^{-1}·y^{-1}.

The gutter design was altered between Exp. 3 and 4 and this may have impacted NH_3 emissions and solids DM. NH_3 emissions and DM content were 1.22 kg NH_3·pig^{-1}·y^{-1} and 45% DM with the trough design, but 0.91 kg NH_3·pig^{-1}·y^{-1} and 53% DM with the duct design. This could be attributable to the gutter design or to the higher average temperatures and lower average humidity in Exp. 2 and 3 (duct gutter) relative to Exp. 4 and 5 (trough gutter). The trough design does offer some unique advantages, namely: it occupies less space and so facilitates retrofits, and it is cleaned each time the belt is operated. Addition of a cover to the trough design could limit airflow across the urine and might help to further reduce NH_3 emissions from the trough gutter, if indeed the gutter is responsible for the changes noted.

Animal performance was evaluated in each of the trials (Table 1). The average daily feed intake (ADFI) was 1.69 ± 0.18 kg·pig^{-1}·d^{-1} and average daily gain (ADG) was 0.83 ± 0.08 kg·pig^{-1}·d^{-1}. The gain to feed ratios (G/F) averaged 0.50 ± 0.02 across the five belt-based housing trials. In Exp. 3, where performance in the belt-based housing was compared to that in conventional flush system barns, there was a significant improvement in the G/F ratio of 5.5% (*P* = 0.01) for the belt-based animals despite the fact that housing density, diet, and animals were matched. Experiments 1, 2, 4 and 5 combined yielded an 11% improvement in feed efficiency when compared to the Exp. 3-Reference or to other trials carried out in the conventional housing system. The reference farm had a lower group size (7 animals·pen^{-1} compared to 16 animals·pen^{-1} in the belt-based facility) necessitated by the desire to match housing density despite different pen sizes. Group size has been shown not to impact the G/F ratio, although larger groups may reduce both FI and growth rate (Hyun and Ellis, 2001; Wolter et al., 2001). Housing environment, however, has been shown to impact pig health and productivity (Donham, 1991). The source of the G/F improvement requires further investigation, but may be due to improvements in air quality resulting from the separate collection of urine and feces. If these improvements are indeed attributable to the housing design, then the belt-based system could result in substantial feed cost savings to producers.

The nutrient loads for various inputs and outputs of the RE-Cycle system were calculated based on consumption and production data for feed and wastes as well as nutrient concentration data for all streams under investigation (TABLE 2). Data for accretion calculations were from Mahan and Shields (1998) for the weight pigs used in our studies. The feed nutrients recovered in the various waste streams plus those calculated as accreted by the animal, show good closure with the nutrients present in the feed consumed. For N, P, K, and Ca, the percent closure is close to or exceeds 90%. For Mg, the lack of accretion data limits conclusions, but the fact that there is 75% accountability in the absence of accretion data is very promising. For Cu and Zn, however, the situation is just the reverse; it seems that more of these nutrients have been recovered than were provided to the animals. Perhaps some copper could have been added through contact of the drinking water with copper pipes. Both of these elements, though, are in very low abundance making it more difficult to segregate the mineral analytical response from the background noise. It is thought that the results shown for Cu and Zn in feces are an overestimation of the amount present and this is probably due to analytical error.

TABLE 2. Nutrient closure from the belt-based housing system.

Component	Intake/Output	Energy	Mineral Ash	Nutrients per pig per day							
	g DM/pig/d	kJ/pig/d	%	units	N	P	K	Ca	Mg	Cu	Zn
IN											
Feed	1690	29925		g/pig/d	49.1	10.8	13.4	12	2.7	0.038	0.259
OUT											
Feces	260	5319	12 – 15	g/pig/d	10.5	5.1	5.1	4.9	2	0.037	0.540
Urine	1320			g/pig/d	9.2	0.2	6.1	0.1	0.0	0.01	0.02
NH_3 Emissions				g/pig/d	2.4						
Accretion				g/pig/d	21.04	3.99	0.632	6.79	UNK	0.001	0.01
OUT / IN				%	**87.9**	**86.0**	**88.3**	**98.3**	**74.7**	**126.4**	**220.3**

GASIFICATION OF SWINE MANURE SOLIDS

Prior to gasification, swine waste solids were analyzed for DM, energy, mineral content, and ash fusion temperature in an effort to understand the probable operating conditions required by this feedstock. At 19.7 MJ/kg DM, swine waste compares favorably with wood (20.2 MJ/kg DM) from an energy standpoint. Waste solids were 45% C, 0.4 % S, and 0.3% Cl^{-1}. Fixed C was 13%; volatile matter, 75%; and ash, 12.2%. The lowest temperature for ash fluidization, seen under oxidizing conditions, was 1218 °C so processing temperatures less than 1000 °C were not expected to cause ash agglomeration problems.

The static system of the BGP gasifier makes it ideal for a wide variety of feedstocks since virtually anything can be loaded into an open cavity for a batch feed reaction. In addition to the swine waste feedstock, the gasifier has thus far processed nursery pig mortalities, poultry litter, chicken and turkey mortalities. Ashes from swine waste solids and poultry litter were compared to the ashes obtained by incinerating pig mortalities (Prestage Farms, grower/finisher, G/F) and by gasifying turkey litter (Energy Products of Idaho), TABLE 3. The data were corrected to an ash only basis for purposes of comparison. High levels of Ca are found in mortality ash in keeping with the bone content of this feedstock. The elevated Cu levels in turkey litter ash may result from dietary levels of this mineral. In short, differences in the ash mineral compositions appear to result from differences in the feedstock rather than from differences in the processing technologies.

TABLE 3. **Comparison of ashes from different feedstocks and from various thermochemical processing technologies.**

Alternative Feedstocks		Corrected to 100% ash—expressed on "ash only" basis					
		%				ppm	
Type	**Source**	**P**	**K**	**Ca**	**Mg**	**Zn**	**Cu**
Hog waste	Ash, gasifier NCSU-BGP	14.34	11.34	16.05	4.97	9044.5	619.4
Chicken litter	Ash, gasifier NCSU-BGP	4.7	4.0	23.3	1.1	0.1	0.02
swine mortalities	Ash, incinerator Prestage G/F	17.45	5.49	27.40	1.22	945.2	480.1
Turkey litter	Ash, gasifier EPI	6.15	3.38	9.76	1.98	586.5	1443.1

Experiments with a pilot-scale gasifier (~70 kg per batch), on loan from BGP, have confirmed its ease of operation. One load can be processed in 3 to 4 h providing a 20 kg/h through-put with this demonstration unit. In order to determine the optimal operating temperature, two trials were performed each day at each temperature ranging from 700°C to 900°C (Table 4). The second trial of each day is reported here in order to compare "steady-state" conditions. From these trials, 800°C was selected as the standard operating temperature since it balanced residence time with propane usage and provided sufficient temperature to guarantee sterile ash and minimal dioxin formation. Since the BGP gasifier is designed to consume its product gases, the only availble energy output is heat from the flue stack. We do not currently have the ability to use this energy, but this heat could be used for steam generation, hot water, heating animal barns, or any other process that needs a high heat source.

TABLE 4. Effect of operating temperature on feedstock processing time and propane use.

Set Temperature	700	750	800	850	900
Feedstock: expired pelleted feed	70 kg at 73% DM	70 kg at 73% DM	70 kg at 73% DM	70 kg at 73% DM	70 kg at 73% DM
Total time, h	3.5	3.25	3.25	3.25	3.75
Total Propane used, cf	85.5	81.9	87.6	96.6	118.3
PC, max, °C	1003	1033	1035	1047	1028

There are several factors that influence the efficiency of the the BGP unit. The feedstock type, DM, feedstock load, and whether the unit was in steady state operation. Data from processing pig mortalities indicate that propane use in a cold start experiment is 3 times that when the unit has been preheated (28.4 cf propane /kg 100% DM feedstock when cold and 9.5 cf propane when preheated).

Recovery of fecal nutrients in BGP gasifier ash has also been evaluated with good results. Gasifying concentrates these nutrients into a mass that is only 17% of the initial feedstock mass (from 260 g manure solids to 44 g pig^{-1}•d^{-1}. The reduced mass has obvious advantages for transport of these nutrients to areas deficient in them. With the exception of Cu and Zn, mineral recoveries were generally in the 80 to 110% range. The Cu and Zn results again suggest that the fecal values obtained for these minerals are spurious. Artificially high fecal values would result in greater than 100% recovery when feces are compared to feed, and substantially lower than expected recovery when ash is compared to feces.

TABLE 3. Nutrient balance from gasification of swine waste solids.

Component	**Intake/Output**	**Energy**	**Mineral Ash**	**Nutrients per pig per day**							
	g DM/pig/d	kJ/pig/d	%	units	N	P	K	Ca	Mg	Cu	Zn
Feedstock IN											
Feces	260	5319	12 – 15	g/pig/d	10.5	5.1	5.1	4.9	2	0.037	0.540
PROCESSED											
Ash$^{\alpha}$	44	612	85	g/pig/d	ND	4.8	4.0	5.3	1.7	0.02	0.29
ASH / FEEDSTOCK				% Closure		**94.5**	**78.3**	**108.1**	**84.2**	**65.6**	**54.3**

Prior to generating sufficient gasifier ash in house, preliminary digestibility trials were conducted with gasified swine waste solids from the EPI process. In vitro solubilities serve to predict bioavailability and are determined by the extent to which ash minerals are soluble in an aqueous solution of HCl at pH 2 (Figure 5). P, K, Ca, and Mg were monitored and all these minerals were very soluble under the conditions described. In vivo, digestibility was determined with 7 pigs in a crossover design. Animals were fed 80g/kg$^{0.75}$ per day of a highly purified (low mineral) cornstarch-casein diet supplemented with either ash or a mineral mix based on monocalcium phosphate, limestone, KOH, magnesium acetate, HCl, and salt. After 5 days of adaptation, feces were collected quantitatively for 3 days before the crossover and repeat. Digestibility was determined as the difference between total intake and total fecal excretion for each nutrient studied. While palatability was a problem, the absorption data indicate that ash minerals are bioavailable and digestibility (Figure 5). Two problems occurred in this preliminary trial: phosphorus was inadvertently over-formulated in the test diet (due to inaccurate analytical results) and an inappropriate, non-digestible source ($MgSO_4$) was used in thecontrol diet. A full scale trial is planned to better confirm digestibility data, pig performance, and pig health when fed ash as a mineral supplement throughout the grow/finish period.

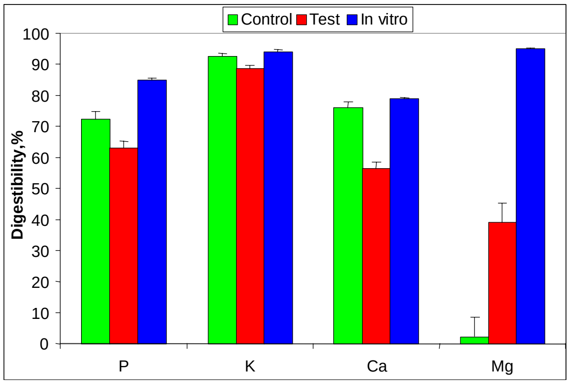

Figure 5. Mineral availability from gasifier ash.

NO_x levels were monitored in the secondary chamber and the flue stack to determine the extent of these emissions to the environment. Flue stack gases are most relevant to environmental impact, but vary with damper opening so that measurements from the secondary chamber were used to follow reaction progress. NO_x levels in the flue ranged from 2 to 20 ppm. NO_x is elevated initially, but decreases after 3 hours of processing as feedstock is reduced to carbon char and mineral ash. Preliminary tests have been conducted to determine the effect of injecting liquid waste into the BGP gasifier secondary chamber to reduce NO_x levels in flue gas as predicted by Pulkrabek (1997). Data obtained were very encouraging since NO_x levels were reduced from over 340 ppm to less than 80 ppm. However, no measure of flue ammonia levels was available during this process, and further testing is required before the exact impact of the procedure can be described. For this reason, the fate of nitrogen has not yet been well characterized throughout the system.

CONCLUSION AND FUTURE DIRECTIONS

Belt-based housing holds promise for reducing emissions from hog buildings, improving pig performance, and facilitating waste nutrient transport to areas of need. Improved feed efficiency may help to improve producers' profitability. The solid material recovered from the belt is ~50% DM and suitable for gasification. A commercial-scale belt installation is a vital component for verifying the benefits observed with the demonstration unit and for supplying sufficient waste to operate the gasifier over extended periods. The BGP gasifier is easy to operate, completely disposes of bioactive molecules and pathogens, and offers the potential of recovering energy from waste heat. The residual ash retains valuable nutrients, such as P, K, and Mg, that can replace mined mineral supplements in feed or be part of a fertilizer blend. More work must be done to optimize the gasification process and reduce secondary fuel use. A continuous feed gasifier is currently under development; it will be operated under steady state conditions which is expected to dramatically enhance efficiency. Addition of steam reforming and product gas capture to the new design will make it possible to modify the product gas composition and recover it for synthesis of biofuels.

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