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Product and Economic Analysis of Direct Liquefaction of Swine Manure

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Abstract Direct hydrothermal liquefaction of biomass is a technology that has shown promising results in treating waste and producing oil. A batch hydrothermal liquefaction system was used to treat swine manure, and it successfully converted up to 70% of swine manure volatile solids into oil and reduced manure chemical oxygen demand by up to 75% (He et al., Trans ASAE 43(6):1827–1833, 2000). A continuous-flow reactor was developed and resulted in similar conversion rates to the batch process, indicating the potential for scale-up (Ocfemia, 2005). This study investigates the hydrothermal process in relation to a livestock system to determine the impact on oil yields and fertilizer values that might be realized in a farm-scale application. Oil products from the hydrothermal process are maximized using manure containing around 20% solids, but typical swine confinement facilities contain wetter manure slurries. A preliminary investigation of liquid–solid separation methods was conducted to determine the resultant oil yields and the effects of the hydrothermal process on fertilizer values in the wastewater as compared to the unprocessed manure. Energy and economic analyses of the liquid–solid separation and hydrothermal liquefaction processes were also conducted. The hydrothermal process results in an oil product as well as a fertilizer product that retains the majority of its nitrogen value with a reduced level of phosphorus (as compared to the unprocessed swine manure). The economic analyses indicate feasibility for several different liquid–solid separation methods, dependent on the equipment and maintenance costs assumed for each method. Conveyor-belt manure collection systems in conjunction with hydrothermal liquefaction are especially promising.

Keywords Bioenergy economics · Direct hydrothermal liquefaction · Swine manure · Thermochemical conversion of biomass · Waste to energy

Introduction

Using waste materials to produce biofuel sidesteps the controversial food-versus-fuel debate and gives the production process a competitive advantage over methods using more expensive traditional feedstocks. It therefore makes sense to research methods of biofuel production from waste streams alongside research of biofuels produced from more valuable feedstocks.

Hydrothermal liquefaction (HTL) is a chemical reforming process in which the depolymerization and reforming reactions of organic matter occur in a heated, pressurized, and oxygen-free or oxygen-deficient enclosure. It is a thermochemical process similar to pyrolysis [12], but it is better-suited for the conversion of livestock waste and algae because it produces oils with higher heating values than pyrolysis oils [23] and the high-pressure environment ensures that any water in the reactor remains in the liquid phase so it does not require the feedstocks to be dry.

HTL has been studied extensively during the past 10 years at the University of Illinois [2, 8, 12–17, 22, 23]. Processing parameters that optimize the oil yield were determined [13]

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and applied to a continuous reaction process to determine the feasibility of scaling the system up beyond the batch scale [23]. The system had a capacity to process up to 48 kg of manure slurry per day and successfully produced oil at equal or greater efficiencies than the batch process.

The desired total solids (TS) content of the feedstock for the HTL process is around 20–25% [15]. This is approximately the TS contained in fresh (i.e., taken directly from the confinement floor) swine manure. However, as noted by Fulhage and Pfost [11], most swine manure is handled as a liquid slurry, utilizing shallow storage pits beneath slotted floors that allow the producer to store the manure and apply it to fields as a fertilizer product only when it is most beneficial. This slurry contains more water than what is optimal for the HTL process, and since additional water translates into additional heating and processing costs, it is important to remove as much water as possible without significantly impacting the oil yield.

Zhang and Westerman [27] reviewed many different liquid–solid separation (LSS) techniques for swine manure, including mechanical separators like the stationary inclined screen, vibrating screen, rotary screen, belt press, and centrifuge, while Chastain et al. [7] investigated the use of a screw press. These techniques were compared in terms of their efficiency at capturing the solids from the original manure slurry, but their effects on the efficiency of the HTL process were not investigated. Not all solids are equally conducive to the formation of HTL oils, so two LSS techniques could remove similar amounts of solids from the slurry but yield different amounts of oil. The potential for HTL as a processing option for swine manure encourages a reconsideration of the different possibilities for LSS—one that takes oil yield into account.

This study aims to compare the effects of some of the different LSS methods on the:

1. Oil production rates
2. Fertilizer value remaining after the HTL process
3. Energy input costs for the HTL process

Determining the effects of different LSS methods on these three variables allows for rough estimations to be made regarding the economic feasibility of a farm-scale system.

Methods

Overview

The general steps followed throughout this study were:

1. Choose an LSS method and apply it to manure slurry.
2. Pool the filtration residues and centrifuge cakes from step 1 and subject them to HTL.
3. Submit the filtrates, centrates, and post-HTL aqueous portion from steps 1 and 2 for fertilizer analysis.
4. Analyze bio-oil from step 2.

Swine Manure Characteristics

The swine manure used in this study was taken from a grower–finisher facility (35–100 kg animal weight) located near the University of Illinois at Urbana-Champaign (Grein Farm, County Road 1300 N, Urbana, IL 61802). This manure was found to contain around 25% TS when taken from the floor and 5–10% TS when taken from the shallow pit. The particular sample of pit manure used in this study contained 9% TS. These values corroborate the numbers given by Fulhage and Pfost [11], although variability is possible for different management practices.

Determination of TS

TS were measured by Midwest Laboratories (Omaha, NE, USA) as part of their fertilizer analysis package. Their results were corroborated in-house by convection heating at 105°C for 24 h in a mechanical convection oven (DKN 400, Yamato Co.). Volatile solids content was measured by feedstock incineration (Barnstead Thermolyme Co. furnace) at 600°C for 3 h or until the weight stabilized.

LSS Methods

Evaporation is an effective method of LSS, but also very time and energy intensive. Based on our previous work (unpublished), evaporative drying of manure slurry results in oil yields essentially equal to those realized by using fresh swine manure, but the energy costs and low throughputs associated with evaporative drying make it infeasible as an LSS method in a farm-scale system. For these reasons, evaporative drying was not one of the methods chosen to include in this study.

Coarse filtration was accomplished using an aluminum screen as the filter medium. The screen had rectangular openings measuring 1.13 × 1.30 mm, and it was used as a liner inside a perforated cylindrical tumbler that was rotated until the flow of filtrate out of the assembly ceased. The filtration residue was collected, and the filtrate was saved for further separation or analysis.

For the low-speed centrifugation, a vertical-shaft solid-basket centrifuge manufactured by Lavin Centrifuge (model 12-413V) was used to subject the filtrate from the coarse filtration to 2,250 relative centrifugal force (RCF; e.g., 2,250 RCF=2,250 times the force of gravity) for 5 min. This corresponded to a rotational speed of 3,000 RPM. The centrifuge cake was collected and the centrate was saved for further separation.

The centrate from the low-speed centrifugation was then centrifuged using a GS-3 rotor (Dupont Sorvall, Newtown, CT, USA) at 10,816 RCF for 15 min. This corresponded to a rotational speed of 8,000 RPM, and it constituted the high-speed centrifuge process. The centrifuge cake was collected and the centrate was saved for analysis.

Table 1 depicts the characteristics associated with the different LSS methods. For each subsequent LSS technique, the filtration residues and centrifuge cakes were pooled and then subjected to HTL.

Another method of raising the TS content (thus lowering the net water content) is by the addition of a drier material to the slurry. In this study, sawdust (95% TS) and miscanthus (89% TS) were tested as additives. In both cases, the additive was mixed with the manure slurry to create slurries with net TS of 20%.

Hydrothermal Liquefaction Process

The HTL was conducted using a batch reactor under similar conditions as those used by He [12] and Ocfemia [22]. The temperature was the main control variable and was held at 305°C for 30 min of residence time in a 2-l reactor (Parr Instrument Company, Moline, IL, USA). The reactor was thrice purged with 689 kPa of nitrogen gas before pre-pressurizing the reactor with 689 kPa of nitrogen gas, which was used as a process gas throughout the experiment.

These operating conditions resulted in a peak reactor pressure of 11,376 kPa when the reactor was at its peak operating temperature. No catalysts were used during these particular tests.

Post-HTL Analysis

The HTL process results in a raw oil product that is crude and unrefined. The raw oil product was separated from the aqueous product by vacuum filtration using a Whatman filter paper with pore size of 11 μm. The water content of the bio-oil was determined using American Society for Testing and Materials (ASTM) standard D95-99 [3] and subtracted from the oil yields.

The toluene solubility was determined using ASTM standards D473-02 [4] and D4072-98 [5] and used to define a “refined oil yield,” which comprised roughly 35–45% of the raw oil product. The refined oil yield gives an idea of both the quantity and quality of the oil and is a more robust measurement of the oil production than the raw oil yield. Oil yields were based on the TS of the feedstocks, including any additives.

Samples of the oil and aqueous phases were sent to Midwest Laboratories (Omaha, NE, USA) for basic and fertilizer analysis using the methods of the Association of Official Analytical Chemists.

Energy Assumptions

The following assumptions were used when calculating energy balances:

- The bio-oil has a heating value of 30,000 kJ/kg [22].
- The energy contained in the feedstocks before undergoing HTL was negligible or unavailable. In other words, it is assumed that the only energy input is heat, and the chemical energy in the feedstock is not considered. In all cases, the manure slurry contained too much water to be burned so this was an accurate assumption for the feedstocks considered.
- Heat loss through the reactor walls was considered negligible compared to the heat required to raise the feedstock temperature to operating conditions.
- The specific heats of the feedstocks are equal or less than the specific heat of water (i.e., the energy needed to raise the temperature of the feedstock to the operating temperature is equal or less than that needed for an equivalent amount of water). This is a reasonable and conservative assumption because the feedstocks contained 75–95% water, and the specific heat of water is higher than most materials. For example, the specific heat of water is over four times that of sawdust. Thus, more energy is needed to heat pure water to a given temperature than would be needed to heat the same amount of water mixed with sawdust or manure.

Table 1 TS and percent of original slurry remaining after subsequent LSS steps

Raw manure slurry—9.2% TS				
LSS step applied	Filtrate/centrate		Filtration residue/centrifuge cake	
	TS	% of raw	TS	% of raw
Coarse filtration	7.72	86.1	18.2	13.9
3K RPM centrifuged	6.76	81.0	23.0	5.10
8K RPM centrifuged	3.00	50.5	13.0	30.5

- The values for the change in internal energy are therefore higher than the actual values, and the actual energy needed to heat the different solutions should be lower than (but close to) what would be calculated using the following values for water. For this reason, the energy input values used in the study are conservative. Also, the difference between enthalpy (which takes into account the energy needed for pressurization) and internal energy for subcooled water at the reaction conditions was 0.7% and even less at every temperature below the operating temperature, so internal energy values were sufficiently accurate. This is because water is very nearly incompressible.
- Reaction conditions are approximately 10,000 kPa and 303°C. From Moran and Shapiro [20]:

$$\text{Internal energy of water at } 303^\circ\text{C}: \quad 1,350.5\ \text{kJ/kg}$$
$$\text{Internal energy of water at } 22^\circ\text{C}: \quad 92.3\ \text{kJ/kg}$$

$$\text{Energy needed to raise feedstock to operating temperature and pressure}:$$
$$1,350.5\ \text{kJ/kg} - 92.3\ \text{kJ/kg} = 1,258\ \text{kJ/kg}$$

- Heat is recaptured via a heat exchanger with an effectiveness of 75%. This is a conservative value considering empirical results of using heat exchangers for processing biomass [9].

Economic Assumptions

For the following calculations, the cost of energy was estimated to be $0.05/kWh. If the reactor was only operated during certain times of the day, this is a reasonable estimate for industrial power costs, although in practice this value will vary. The HTL process primarily requires energy in the form of heat rather than electricity, and this energy could be supplied via combustion of natural gas, which has an industrial cost under $0.02/kWh as of May, 2011 [25]. For these reasons, an energy cost assumption of $0.05/kWh is conservative.

The value of crude oil varies greatly and since the value of the bio-oil will be somewhat correlated to the price of crude oil, the value of the bio-oil can also be expected to be volatile. For example, in just a 12-month span from winter of 2008 to winter of 2009, the price of oil varied from $40 to $140 per barrel. The price of petroleum crude oil as of May 2011 is $101 per barrel [26].

Estimating the precise value of the bio-oil in relation to crude oil is difficult due to uncertainties regarding the costs involved in refining the bio-oil. Alternatively, the bio-oil might be considered for use as an asphalt binder replacement [10]. Appleford [2] analyzed the bio-oil from the HTL of swine manure and found that the bio-oil was primarily resins and asphaltenes, as seen in Table 2. Asphaltenes are, broadly speaking, insoluble in heptane or pentane and soluble in benzene/toluene.

The pooled sample of bio-crude from the swine manure contained around 55% asphaltenes and 36% resins. This is further evidence that the value of the bio-oil can be estimated by assuming the products will be used as asphaltenes rather than as a more refined oil product. Asphaltenes are the least valuable of the petroleum fractions, so this assumption is also conservative.

Asphalt prices, like oil prices, can fluctuate dramatically. From January 2008 through July 2011, the price of asphalt binder fluctuated between $386/tonne to $874/tonne [21]. The price as of July 2011 is $669/tonne. Throughout this paper, bio-oil used as an asphalt binder is conservatively assumed to have a value of $375/tonne. Importantly, the use of the bio-oil as an asphalt binder would eliminate many of the expenses, technological hurdles, and uncertainties associated with refinement of the oil and finding a market for the finished product.

The net present value (NPV) of an investment is a standard method for using the time value of money to appraise long-term projects. Essentially it involves calculating the sum of the present values of future cash flows based on an assumed discount rate (or the expected interest rate of investment alternatives), and if the NPV is a positive number, the investment is considered favorable to the investment alternatives. The NPV for a given set of cash flows can be calculated with a few assumptions:

> Labor costs were limited to $35,000 per year per 10,000 hogs.
> The annual discount rate (i.e., the rate of return of investment alternatives) is assumed to be 15%.
> The life expectancy of the equipment is considered to be 10 years.

Table 2 Properties of bio-crude oil from swine manure vs. natural crude oil [2]

Fraction (%)	Bio-crude pooled sample	Natural crude oil	Natural bitumen
Saturates	1.32	>30	15
Aromatics	1.60	>30	34
Resins	35.87	<20	34
Asphaltenes	54.81	<10	17
Water+loss	6.40	Varies	Varies

Results

LSS Techniques

Table 3 details the percentage of the original TS captured by each subsequent processing step. The "Cumulative solids captured" column conveys the amount of solids from the original slurry that remain in the filtration residues or centrifuge cakes after the cumulative LSS techniques. The "Pooled sample TS" column conveys the TS of the pooled sample of filtration residues and centrifuge cakes resulting from the cumulative LSS techniques.

The "Cumulative material captured" column reflects the mass of the combined filtration residues and centrifuge cakes in relation to the mass of the original manure slurry. This is the amount of material that will be subjected to HTL compared to the amount of original manure slurry that would have been subjected to HTL had LSS techniques not been employed. It includes the mass of the water that remains in the filtration residues and centrifuge cakes after the LSS techniques because the remaining water will affect the energy requirements of the HTL process. The "Refined oil yield" is also based on the pooled samples resulting from the cumulative techniques, rather than the samples from each LSS step.

Oil Yields

Figure 1 shows the summarized results of the HTL tests using swine manure and a variety of different LSS methods in terms of their refined oil yields. Figure 2 depicts the differences in energy requirements associated with a given unit of oil production. Figure 3 depicts the energy balances of the oil production process in terms of HTL energy input versus oil-based energy output with and without utilization of a heat exchanger.

Fertilizer Effects

The data are arranged in Fig. 4 according to four cases, which represent several different options of utilizing swine manure as a fertilizer product:

Case 1	Raw swine manure from shallow pit. This can be considered the baseline case or status quo, as it represents the fertilizer value of the swine manure from a shallow pit applied directly to the field without any HTL processing.
Case 2	Aqueous solution remaining after HTL of raw swine manure from a shallow pit. This represents the fertilizer value available if all the manure slurries from a shallow pit were processed using an HTL reactor with no LSS.
Case 3	Raw swine manure from a shallow pit is subjected to coarse filtration. The filtration residue is subjected to HTL processing. The filtrate is mixed with the aqueous solution remaining after the HTL process and applied to the field.
Case 4	Raw swine manure from a shallow pit is mixed with miscanthus to achieve a slurry with a net TS of 20%, which is then subjected to HTL processing. The aqueous solution remaining after the HTL process is applied to the field.

Economics

The preliminary NPVs for the case of fresh manure and for several other cases are summarized in Tables 4 and 5. All the NPVs assume the incorporation of a heat exchanger and the use of the oil product as an asphalt binder. The "Capacity" column illustrates the annual amount of wet manure or manure slurry processed via HTL for each system. The values in this column can be used to estimate the equipment and maintenance costs required for the different systems, but these costs *have not* been included in the preliminary NPV values in Table 4 or Table 5 and will have to be considered when choosing between the different LSS or additive techniques. Initial equipment costs can be subtracted directly from the preliminary NPV values, while maintenance and other annual costs can be subtracted from the yearly profits to calculate a comprehensive NPV value. The NPV values were calculated assuming a 10-year project lifespan with a 15% discount rate.

Table 3 Proportion of original solids in manure slurry captured by subsequent LSS steps

LSS technique	Cumulative solids captured (%)	Pooled sample TS (%)	Cumulative material captured (%)	Refined oil yield of pooled sample (%)
Coarse filtration	27.3	18.1	13.9	24.4
3K RPM centrifuge	40.0	19.4	19.0	26.7
8K RPM centrifuge	83.1	15.5	49.5	31.3

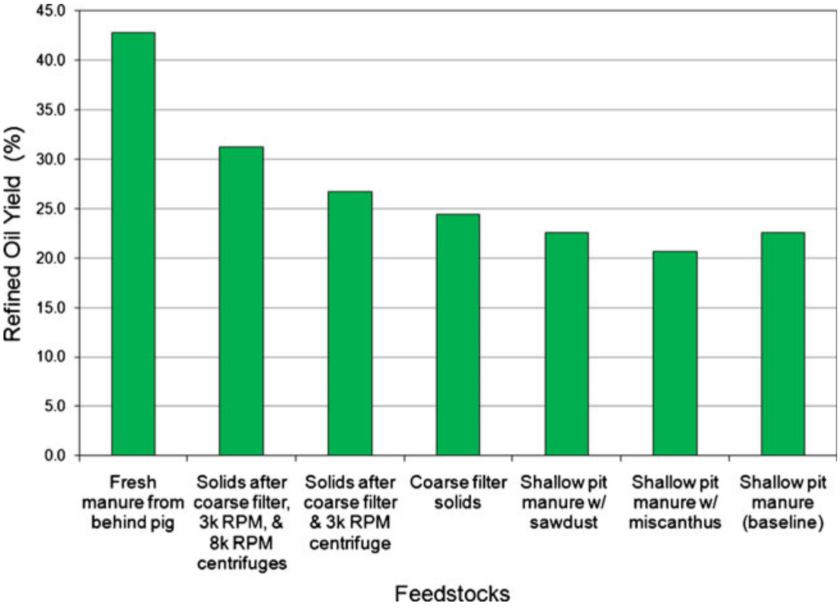


Fig. 1 Refined oil yields

Discussion

Oil Yields

As might be expected, Fig. 1 shows that utilizing more intensive LSS techniques results in oil yields more similar to the oil yield of fresh manure. Presumably this is because each LSS step reclaims more of the components from the original manure. However, the refined oil yield is not the only variable determining a successful HTL process. Certainly energy input costs and equipment costs have a significant effect on the economics. For a feedstock with low TS, a significant amount of energy is spent heating and pressurizing water in addition to the relevant solids, and this energy expenditure is not captured in Fig. 1 because the refined oil yields are based on the weight of the dry solids that enter the reactor—they do not reflect the amount of water that is processed. For example, manure slurry taken straight from the pit and sent to the reactor without any LSS suffers from its high water content, and this should be considered when choosing an LSS method.

Figure 2 takes the amount of water into account and paints a more comprehensive picture of the amount of oil produced relative to energy input costs. In Fig. 2, the different LSS methods are compared according to the number of units of wet feedstock that must be processed

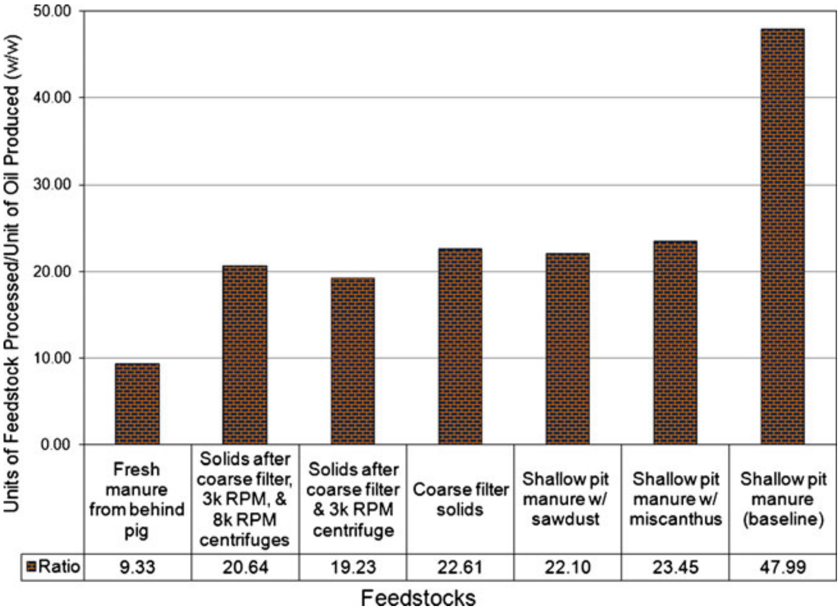
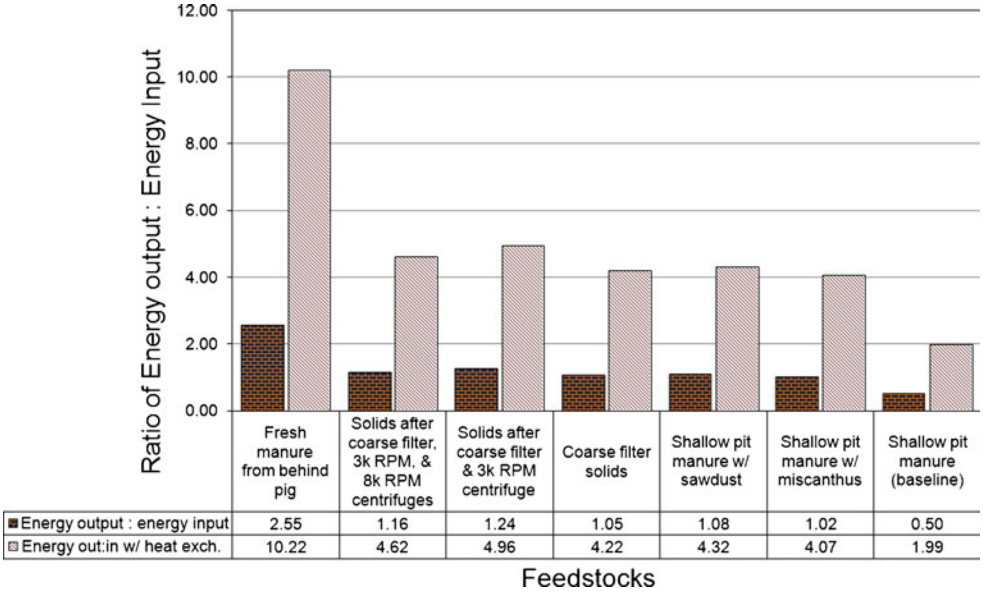


Fig. 2 Relative energy costs per unit of oil production

Fig. 3 Energy output versus energy input



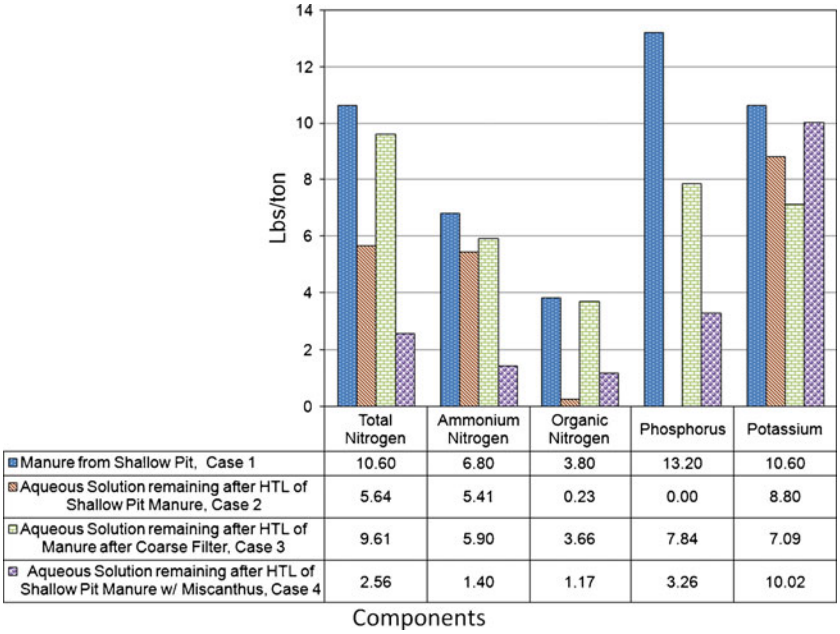
	Fresh manure from behind pig	Solids after coarse filter, 3k RPM, & 8k RPM centrifuges	Solids after coarse filter & 3k RPM centrifuge	Coarse filter solids	Shallow pit manure w/ sawdust	Shallow pit manure w/ miscanthus	Shallow pit manure (baseline)
■ Energy output : energy input	2.55	1.16	1.24	1.05	1.08	1.02	0.50
▨ Energy out:in w/ heat exch.	10.22	4.62	4.96	4.22	4.32	4.07	1.99

to produce a unit of oil. Since processing a unit of feedstock represents an energy cost, smaller values of this ratio are desirable.

In Fig. 2, three “tiers” of performance are distinguishable. The fresh manure comprises the first tier with a ratio of around 10 units of feedstock processed per unit of oil produced. Tier two is occupied by the LSS methods, which are all grouped within roughly 10% of a ratio of 21. These ratios demonstrate the fact that it takes about twice as much energy to produce a unit of oil using post-LSS feedstocks as it would to produce a unit of oil using the fresh manure (a ratio of 21 vs. a ratio of 10). Finally, the manure slurry taken directly from the shallow pit occupies the third tier and uses over twice the energy per unit of oil production as any of the second tier methods and nearly five times as much energy per unit of oil production as would be needed if using fresh manure. This is due to the low TS of the pit manure slurry, which means that large amounts of water are processed for every unit of processed solids.

Since the ratios of the second tier are relatively similar, other considerations come into play when deciding between them. For instance, processing the slurry with a coarse filter, a 3,000-RPM centrifuge, and an 8,000-RPM centrifuge requires more equipment and energy than simply using a coarse filtration process or mixing in a dry additive, so these additional processing costs should be taken into consideration.

Fig. 4 Fertilizer values for different cases



	Total Nitrogen	Ammonium Nitrogen	Organic Nitrogen	Phosphorus	Potassium
▨ Manure from Shallow Pit, Case 1	10.60	6.80	3.80	13.20	10.60
▨ Aqueous Solution remaining after HTL of Shallow Pit Manure, Case 2	5.64	5.41	0.23	0.00	8.80
▨ Aqueous Solution remaining after HTL of Manure after Coarse Filter, Case 3	9.61	5.90	3.66	7.84	7.09
▨ Aqueous Solution remaining after HTL of Shallow Pit Manure w/ Miscanthus, Case 4	2.56	1.40	1.17	3.26	10.02

Table 4 Summary of preliminary NPVs and annual cash flows for different LSS techniques

LSS technique	Income from oil	Processing costs	Labor	Capacity (tonnes)	Preliminary NPV
10,000 hogs					
Coarse filtration	$65,300	$17,179	$35,000	3,772	$65,853
3K RPM centrifuge	$104,400	$23,483	$35,000	5,403	$230,449
8K RPM centrifuge	$254,750	$61,179	$35,000	13,967	$795,831
Fresh manure	$409,867	$44,525	$35,000	10,195	$1,657,908
50,000 hogs					
Coarse filtration	$326,502	$85,895	$175,000	19,676	$329,266
3K RPM centrifuge	$522,002	$117,415	$175,000	27,017	$1,152,244
8K RPM centrifuge	$1,273,751	$305,895	$175,000	69,836	$3,979,158
Fresh manure	$2,049,333	$222,625	$175,000	50,975	$8,289,540

It is very important to consider that raw oil yields are generally two or more times greater than the refined oil (i.e., the toluene-soluble portion of the raw oil) yields used to generate Tables 4 and 5. If the bio-oil is used as an asphalt binder, the raw oil yield (rather than the refined oil yield) may do a better job of approximating the amount of asphalt binder production, since asphalt binder is not a highly refined product. If so, the yields (and income) would be roughly doubled from the values used in this paper. This would have significant economic implications, so it is important to determine exactly how much of the raw oil yield is suitable for use as an asphalt binder.

Fertilizer Effects

The amounts of ammonium nitrogen and potassium available for fertilization do not appear to be severely diminished by the HTL process, as evidenced by the small difference between the values for cases 1 and 2 in Fig. 4. Over 70% of the total excreted nitrogen is contained in the urine stream [1], and it appears that it remains in the aqueous portion as it passes through the HTL process. However, organic nitrogen and phosphorus are nearly eliminated from the aqueous solution (and no longer available to be used for fertilization) when all of the original manure slurry from the pit is subjected to the HTL process.

Case 3 involves the use of coarse filtration before HTL processing, and it appears that most of the organic nitrogen and about half of the phosphorus remains in the filtrate. Since the filtrate is never subjected to HTL, the organic nitrogen and a portion of the phosphorus remain available for fertilization purposes.

Figure 4 also shows that when additives are used to raise the TS, the post-HTL aqueous solution contains similar potassium levels as the raw manure slurry but diminished nitrogen and phosphorus concentrations (about one quarter of the original amount). However, the capacity data from Tables 4 and 5 show that between 2.3 and 8.7 times more solids are processed when additives are used instead of the LSS techniques. The LSS techniques cannot capture all of the solids from the original slurry whereas the additive techniques utilize all of the original solids in the slurry plus the solids from the additives themselves. Thus, the overall amounts of available fertilizer components could be increased even if their concentrations are reduced.

Table 5 Summary of preliminary NPVs and annual cash flows for raising TS using additives

Additive technique	Income from oil	Processing costs	Labor	Capacity (tonnes)	Preliminary NPV
10,000 hogs					
Sawdust, $30/tonne	$550,174	$266,464	$35,000	32,471	$1,248,220
Sawdust, $50/tonne	$550,174	$349,563	$35,000	32,471	$831,165
Miscanthus, $50/tonne	$509,480	$369,968	$35,000	32,833	$524,521
Miscanthus, $60/tonne	$509,480	$415,282	$35,000	32,833	$297,100
50,000 hogs					
Sawdust, $30/tonne	$2,750,872	$1,332,320	$175,000	162,355	$6,241,100
Sawdust, $50/tonne	$2,750,872	$1,747,815	$175,000	162,355	$4,155,826
Miscanthus, $50/tonne	$2,547,399	$1,849,840	$175,000	164,165	$2,622,603
Miscanthus, $60/tonne	$2,547,399	$2,076,410	$175,000	164,165	$1,485,500

The fertilizer values are important because they show that a farmer can use HTL to process manure into bio-oil and still utilize most of the manure slurry's original nitrogen and potassium content as a fertilizer. Additionally, less phosphorus is applied to the field after the HTL process, lowering the risk of undesirable phosphorus runoff, which is a problem faced by some farmers who intensively apply livestock manure as a fertilizer.

Economics

The NPVs listed in Tables 4 and 5 indicate that using HTL to process swine manure is feasible for large production facilities. Especially promising are the economics involved with collecting the manure before it is diluted with water and urine, and serious consideration should be given to coupling an HTL system with a conveyor-belt manure collection system [18] that can collect manure at above 30% TS for HTL processing while simultaneously improving the air quality in the production building, leading to higher rates of weight gain for the pigs.

Even without an alternative collection system, several of the LSS and additive techniques show promising economics on larger operations, especially considering that these NPVs do not include any of the remaining fertilizer value after the HTL process. Since most of the fertilizer value appears to remain in the aqueous portion, including this value could further improve the economic outlook of the HTL processes. The aqueous portion also holds promise as a source of nutrients for algae that can clean the wastewater stream before undergoing HTL to produce more bio-oil from the same system.

These NPVs are dependent on the value of the bio-oil product, so an important next step in the development of farm-scale HTL systems is the determination of the value of the bio-oil as an asphalt replacement. If the bio-oil was not used as an asphalt binder and another value for the oil was calculated instead, the values for "Income from oil" in Tables 4 and 5 can be multiplied by a factor of 1.60% of the dollar value of a barrel of bio-oil.

Corn stover could also be considered as a potential additive, since it would likely yield more oil than miscanthus [24] and is abundant in swine-producing areas. Corn stover costs in Indiana average $42–50/tonne corresponding to transportation distances of 5–50 miles [6], while switchgrass costs average $64–72/tonne for equivalent transportation distances and miscanthus costs average $41–58/tonne at the farmgate in Illinois [19]. These costs are similar to the ones used for miscanthus in Table 5, so it is expected that the NPVs using these different additives would be similar to those for miscanthus.

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