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Editors
W. Christopher Scruton
Stephen Claas

Layout
David Brown

Cover Design
Ruth Cronje, and Jan Swanson;
based on the original design by Dr. Robert Dunlop

Manure as a value-added product

Jose R. Bicudo, Ph.D

Dept. of Biosystems and Agricultural Engineering, University of Minnesota-Twin Cities

Intensive livestock farming's rapid growth in recent years has resulted in a surfeit of animal manure. Specialization and intensification have been the major changes in animal husbandry and poultry production over the past 20 years. The need to improve animal performance and labor efficiency in order to meet the escalating demands for low cost animal products has led to mechanization of various operations (feeding, watering, etc.) with a consequent trend toward animal confinement. These developments have aggravated manure disposal problems as the increased number of animals is coupled with increased concentration of manure in relatively small areas. For ease of handling, excreta are usually removed as liquid slurries, which are then disposed of mainly by land application. Although this practice will remain the primary approach to disposal and utilization of manure for most systems in the foreseeable future, many alternatives to this approach have been proposed, and several have been adopted to a lesser or greater extent. Also, it is being well recognized that manure has the potential to be either a valuable resource or a major pollutant, depending on how it is managed. The objective of this paper is to provide a brief overview of how manure can be managed and/or treated in order to obtain a value-added product.

Manure characteristics

In any discussion on materials handling it is important to have access to reliable data on the characteristics of the material being handled. This requirement is no less valid for animal manure than for any other product requiring collection, storage, and transport. It is also important to be aware of factors likely to influence the properties of the particular material (Robertson, 1977). Manure characteristics are affected by a variety of factors, many of which are unique to a specific farming operation. Not only does the species of animal influence the properties of manure produced, but also within species there are wide variations. Pregnant animals produce manure that differs both in chemical composition and in volume from that produced by lactating animals. Food and water intake, as well as the composition of the ration, significantly influences the volumes and proportions of urine and feces produced. Environmental conditions and management also influence the properties of the material handled.

Swine manure is most often handled as liquid slurry in most confinement operations with dry matter content ranging from 1–10%. Manure from hoop structures with deep straw bedding has generally highly variable characteristics depending on the dunging locations. The dry matter content of solid manure is usually greater than 20%.

The four main categories of compounds in swine manure are as follows:

- organic compounds, partly dissolved and for a large part present as suspended solids;
- nitrogen-containing compounds including ammonia, mostly dissolved;
- phosphorus-containing compounds for a large part present in the suspended fraction; and,
- minerals such as potassium, sodium, chloride, calcium, magnesium, sulfate (mostly dissolved).

The chemical properties of manure of most concern to the farmer are those related to the quantities of nutrients contained in manure. Several tables published from many different sources are available for the estimation of the approximate amount of nutrients in manure. Because each manure pile or pit is unique, the table values are only meant to be approximate rather than accurate data. **Table 1** contains nutrient analysis of swine manure collected from 230 farms in Minnesota between 1994 and 1997.

Table 1. Nutrient content of swine manure in Minnesota (Schmitt, 1999)

Facility	Liquid (lb/1000 gal)			Solid (lb./ton)		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Farrowing	27	27	15	N/A	N/A	N/A
Nursery	34	25	18	N/A	N/A	N/A
Gestation	40	42	18	22	27	14
Finishing	53	39	29	22	22	17

A recent study on a hoop structure for grow-finish swine showed bedding moisture varied from 23% to 75%, nitrogen content ranging from 11 lbs./ton to 36 lbs./ton, phosphorus from 13 lbs./ton to 40 lbs./ton, and potassium from 12 lbs./ton to 51 lbs./ton (Richard *et al.*, 1998). The total amount of nutrients in manure is not as important as the availability of these nutrients. According to Schmitt (1999), 80% of the P and 90% of the K in animal manures are available the first year.

Nitrogen availability is more complex to estimate in manure than P and K due not only to the several transformations that occur in the soil, but also to the method and time of application. In addition, plant uptake and use depend on a series of factors such as species, climatic and soil conditions. It has been estimated that 70–80% of nitrogen in swine manure is available in the first year when applied by injection methods in Minnesota (Schmitt, 1999).

Both nitrogen and phosphorus can adversely affect the environment if not properly managed. Surface runoff and soil leaching of nitrates and phosphates can cause long-term problems with pollution of both ground and surface waters (Fallowfield *et al.*, 1994). Atmospheric release of ammonia has also led to increasing environmental concerns.

Besides providing valuable nutrients to the soil, including all micronutrients, manure supplies organic matter to soils. This improves soil tilth, aids in the retention of water and nutrients, lessens wind and water erosion, and promotes growth of beneficial organisms. On the other hand, the organic matter content of manure is responsible for acute water pollution incidents and for odor problems. The readily degradable material is measured by the biochemical oxygen demand (BOD). The total organic matter content is measured by the chemical oxygen demand (COD). Odor problems largely arise from volatile organic compounds produced during the anaerobic fermentation of manure. A finishing pig weighing between 150 lbs and 200 lbs. can produce as much as 0.6 lbs. of BOD/day (MWPS, 1993). If the total manure production from a finishing pig is about 1.4 gal/day, then the organic matter concentration measured as BOD will be over 40,000 ppm. Therefore, spills or runoff of liquid animal manure directly into water have an immediate environmental impact, threatening fish and other aquatic life. In addition, the excessive growth and decay of algae and other aquatic organisms that feed on excessive nutrients in water deplete dissolved oxygen. The resulting hypoxia (low oxygen) from chronic nutrient enrichment can result in fish kills, odor, and overall degradation of water quality. Serious spills of animal manure into waterways have occurred frequently in recent years both in developed and developing countries. In the UK, for example, the majority of reported pollution incidents are due to the escape of animal slurries or silage effluents. About 9% of all water pollution incidents reported to the British National River Association (NRA) in 1990 were caused by animal manure and one third of those were considered to be of major significance.

Manure's value as a fertilizer

The value of manure is usually usually understood in terms of the cost of any commercial fertilizer it replaces. Information is collected on nutrients available in manure and nutrients required by crops for each field on a farm in order to determine the fertilizer replacement value of manure. A manure application plan is developed and the commercial fertilizer bill with and without manure application is estimated. The difference between these two numbers is called the economic value of manure (Levins *et al.*, 1996). Storage, handling, and application costs must also be included in the calculation.

Another aspect that has to be taken into consideration is the economic value of manure nutrient testing. The difference between using actual and estimated nutrient values for manure can be several thousand dollars in the fertilizer bill. About 5 years ago, only a handful of farmers in Minnesota were testing their manure. Currently, many farmers are having their manure tested on a frequent basis, thanks to the Extension Services's educational efforts and programming. It is obvious that both money and time invested in manure testing have shown substantial economic and environmental benefits.

An example is given in **Table 2** on the value of manure as a fertilizer for a 2,000-head finishing pig farm with different land sizes available. Fertilizer recommendations were based on a 140 bu/ac corn yield after soybean crop on a medium/high organic matter soil. Land application is by sweep injection. Other assumptions include a P soil

Table 2. Value of manure as a fertilizer

Land (acres)	Demand (lb./acre)			Supply (lb./acre)			Excess (lb./acre)			Value ($1,000)		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
200	100	40	61	260	190	143	160	150	82	4	2.0	1.6
500				104	76	57	4	36	(3)	10	5.0	3.8
1,000				52	38	29	(48)	(2)	(32)	10.4	9.6	3.8

Obs.: values in parenthesis indicate shortage of nutrient.

test of 12ppm and K soil test of 100ppm, \$0.20/lb of N, \$0.25/lb of P, and \$0.13/lb of K. All calculations were based on values given by Schmitt (1999). Storage, handling, and application costs were not included in this example.

In some cases manure may have no value at all. It has been estimated, for example, that costs exceed \$200.00 per cow per year in excess of fertilizer value for smaller dairies in the State of New York (Jewell *et al.*, 1997).

Biogas generation

Intensive livestock production systems are poor converters of fossil energy. Fossil energy is a major input to such systems, mainly indirectly for the production of feed. It has been shown that feed accounts for 72–74% of the total energy input (Haan et al., 1996). Energy output for livestock products comprises food and non-food items. Southwell and Rothwell (1977) estimated output/input ratios of 0.38, 0.11, and 0.32 for pork, poultry meat, and eggs, respectively. The ratio was about 0.5 for milk. A large portion of non-food energy output is in the form of manure and the potential for recovery of this energy has greatly increased in the last 20 years.

Biogas plants have been established for the anaerobic processing of concentrated wastewater from agro-industry, of animal manure, and also of municipal wastewater. A consortium of microorganisms participates in numerous processes that convert diverse complex organic substances into simpler forms, including carbon dioxide (CO_2) and methane (CH_4). Depending on the substrate, hydrogen sulfide (H2S) and considerable ammonia (NH_3) may be formed, both of which may accumulate to concentrations that can inhibit methanogenic activity.

Methane gas at standard temperature and pressure has a net heating value of 960 BTU/ft^3. Because biogas from animal operations is typically between 60% and 80% CH_4 (the remaining composition is primarily CO_2, with trace quantities of H2S and water), the low heating value of biogas is approximately 600 BTU/ft^3. Natural gas, which is a mixture of methane, propane, and butane, has a low heating value of approximately 1,000 BTU/ft^3.

With some equipment modifications to account for its lower energy content and other constituent components, biogas can be used in all energy-consuming applications designed for natural gas. The most common use is to have it burned in an internal combustion engine to generate electricity. Lusk (1998) indicated that electrical conversion efficiency of 25–40% is possible with currently available engines. When biogas is used to produce electricity, there is the added potential for harvesting hot water and steam from the engine's exhaust and cooling systems. Combining hot water and steam recovery with electricity generation may provide an overall conversion efficiency of 80% or more. Biogas is also burned in boilers to produce hot water and steam used for heating of animal operations.

Biogas can be also successfully compressed for use as an alternative transportation fuel in light- and heavy-duty vehicles. In order to use methane as a fuel, the biogas is scrubbed of its CO_2, H2S, and water. After scrubbing, the technique of fueling with biogas is basically the same as that used for compressed natural gas vehicles. In many countries, biogas is viewed as an environmentally attractive alternative to diesel and gasoline for operating local transport vehicles, buses, and other public service cars.

Compared to digester influent composition, the treated effluent composition has 2–5% less volume, the same N, P, and K, and fewer odors. Note that in an economic evaluation of digestion, nutrients cannot be considered since these nutrients are present whether a digester is used or not.

The economics of digestion take into consideration operation size (larger is more economical), energy price (propane, fuel oil, and/or electricity), energy savings vs. energy selling, new vs. used equipment, labor cost, replacement costs, and odor control value with no cost savings for fertilizer value. Minimum operation size to consider installing an anaerobic digester is about 250 milking cows, 400 sows farrow-to-finish, or 100,000 layers. Electricity production from a farrow-to-finish operations is estimated to be about 2 kWh/sow-day (Parsons, 1984).

According to Lusk (1998), surveyed farmers who have installed and continue to operate digesters are generally satisfied with their investment decisions. Some chose to install digesters for non-economical reasons, primarily to control odor or contain excess nutrient runoff.

On the other hand, the performance data does not appear to be encouraging to a farmer who is considering whether to install an anaerobic digestion system. Overall, the chance of failure (i.e., the chance of having a non-operating digester) is about 50% in the U.S. (Lusk, 1998). The failure rates for complete-mix and plug-flow technologies are 70% and 63%, respectively. The list of reasons explaining why some anaerobic digesters fail is probably headed by bad design and installation. Poor quality equipment and materials selection is the second most common reason for failure.

One encouraging note is that the reliability of digesters built since 1984 is far better than for those constructed in the period between 1972 and 1984. This is generally due to a resurgence of interest in farm-based anaerobic technology and the development of more simplified digester design.

Unfortunately, biogas production may remain unattractive to farmers as long as the price of fossil fuels remains low. However, if anaerobic digestion of manures becomes a component of a total manure management system, biogas production may become more attractive. According to Lusk (1998), without the environmental benefits provided by anaerobic digestion technology, some farmers might have been forced out of livestock production. Anaerobic digestion is probably one of the few technologies that allow growth in the livestock production business. Turning a waste liability into a profit center that generates annual revenues can moderate the impacts of declining commodity prices and diversify farm income.

Composting

Composting solid manure or separated manure solids with other farm or community by-products for use as soil amendments or organic fertilizers provides a valuable outlet for land-limited farms as well as a service to a community having trouble disposing of shredded paper, yard waste, leaves, wood chips, etc.

Although composting is a relatively expensive and labor intensive process, most of the operations that were established in dairy farms, for example, are self-contained. Farmers compost the manure produced in their farm, manage the effort themselves, and own the finished product. Factors relating to the quality, handling, and distribution of manure contribute most to their decision to start and continue a composting operation.

Composting is an aerobic, biological process in which microorganisms convert organic materials such as manure, sludge, leaves, paper, and food wastes into a soil-like material called compost. It is the same process that decays leaves and other organic debris in nature. It offers several potential benefits including improved manure handling, enhanced soil tilth and fertility, and reduced environmental risk. The composting process produces heat, which drives off moisture and kills pathogens and weed seeds. However, these benefits currently offer little incentive for large-scale, farm-site composting of most animal manures.

Because the use and sale of compost are usually seasonal, there is a need to provide storage for compost produced continuously. Finished compost that has been properly composted and cured has a low, but still on-going rate of microbial activity. It may develop anaerobic conditions if stored in large piles. As with curing piles, good management is essential to prevent the development of wet and anaerobic conditions in the storage piles.

In addition to the material handling steps, several secondary operations are sometimes necessary to condition or to improve the compost qualities for sale or use. These may include screening, drying and bagging. Screening improves the quality of the compost by removing unwanted objects, clumps of compost, and material that is not fully composted. It also recovers the bulking agent from the compost for reuse. Drying lowers the moisture content of the compost. If necessary at all, drying is most important where compost is used for bedding, as a litter ingredient for floor-managed poultry operations, as potting soil or packaged in bags. Drying typically involves extra aeration or an extended composting period. Bagged compost brings a higher price than compost sold in bulk and can be practiced when the sales volume justifies the equipment and effort.

Odor is perhaps the most common problem associated with composting, and failure to adequately address it has led to numerous neighbor complaints and the closure of many large-scale facilities. Fortunately, for the most part odors can be controlled, but proper management can take time and money.

Recent efforts at using earthworms to stabilize a mixture of animal manure solids and crop residues yielding a marketable vermicompost by-product have been quite successful. The end product is a fine material with good structure, porosity, aeration and moisture retention capacity. Unlike conventional composting, organic material that is degraded by worm composting does not reach high temperatures. The process is more sensitive than ordinary composting, however, and requires more attention as well as being able to handle only relatively small quantities of homogeneous waste material.

Processed manure as feed products

Recycling processed manure as feedstuffs makes direct use of protein, amino acids, and fiber that otherwise would be lost were the manure applied to soil. Most re-feeding work has been directed toward making recycled feedstuffs for ruminants, which have the ability to digest high fiber products that are of low value to other livestock species. However, re-feeding is not a universally acceptable practice. In fact, it is considered unnatural and it is banned in most European countries. In the U.S., more than 20 states have regulations that permit the marketing of animal manure as a feed ingredient (Hauck, 1995).

Several important considerations should be made before a decision is made to attempt re-feeding of processed manure to cattle, including the product's moisture content, nutrient density, local availability, handling, processing and storage needs, possible regulations restricting use, and the potential for presence of pathogens, toxins, or chemical residues.

Recently there has been interest in the feeding of screened solids from swine manure. The material is usually from screen and screw-press separators. Composition of separated solids from flushed swine manure are given in **Table**

3 along with the requirements of a steer gaining 2.0 lbs./day.

The experimental data shown above was gathered on a preliminary basis only through a few trials. The separated solids from swine manure would be classified as a concentrate, which would make it a substitute for corn in the ration of a growing calf. Based on its estimated energy and protein value, separated solids could be worth $38.00/ton (wet basis). But because of the increased cost of handling and storage of this type of material, it may only be worth about $19.00/ton (wet basis) (Poore, 1997).

Apparently, there is great potential to separate swine manure, mix the separated solids with other locally available by-products, and process them into commercially viable feed ingredients. Lindley (1982) summarizes research results regarding manure processing for feed components. Processing of animal manure is important for destruction of pathogens, improvement of storage characteristics, and maintenance or improvement of palatability. Many different processing methods have been studies during the 1970s and early 1980s. The more complex chemical treatments can produce high quality feed components, but they are difficult to implement on a farm. Biological processes, such as ensiling (acid fermentation) are more practical and result in a feed that is palatable and safe. Based on previous research, the United States FDA (Food and Drug Administration) has concluded that the use of animal manures does not present a health hazard to animals fed such rations or to consumers of food derived from these animals (Taylor and Hansard, 1981). Currently, there are many conversion processes using microorganisms being studied.

Biomass production

The major biological agents that have been employed in research and development programs for the production of biomass from animal manures are microorganisms, such as bacteria, fungi, and algae. Some of the advantages of using these microorganisms for biomass production include (Seal, 1992):

- diverse metabolic activities to utilize and grow in a range of substrates;
- short generation times and thus large amounts of biomass can be produced in a short period; and,
- the technology used for their mass culture is already established in industries such as brewing and food.

Plants, such as duckweeds (plants within the *Lemnaceae* genera) and water hyacinths, have also being used for the production of biomass.

A referenced list of plants and microorganisms used in biomass production from animal manures is shown in **Table 4**. This is not an exhaustive list, but gives an idea of some of the work that has been done mainly during the 1980s and also some of the most recent work in the area of biomass production using bacteria, fungi, algae, and plants.

The intensive use of microalgae for the treatment of organic liquid wastes was pioneered by Oswald and coworkers (e.g. Oswald, 1963). Microalgal wastewater treatment systems aim at optimization of photosynthetic oxygen production. Oxygen production is related to algal growth rate. High-rate algal ponds are used for algal biomass production. Intermittent daily mixing is provided in order to resuspend settled solids and promote algal growth and photosynthetic oxygenation. Algae are cultured not in slurries of raw manure, but in previously treated or diluted liquid fractions of swine manure. Algal biomass productivity can be high, up to 0.006lb dry matter (DM)/ft^2-day, but productivity about 0.004lb DM/ft^2-day is likely more sustainable. The biomass from high rate algal ponds treating pig slurry has a nutritional value similar to casein or soyabean meal (Fallowfield and Garrett, 1985). **Table 5** shows protein production by algae compared with other feedstuffs.

Table 3. Composition of separated solids from swine manure and the requirement of a growing steer calf (adapted from Poore, 1997)

Parameter	Steer requirement	Separated solids		
		Screw-press	Screen 1	Screen 2
Dry matter, %	N/A	30.7	24.5	26.5
Crude protein, %	12.0	11.1	11.9	18.0
TDN, %	69	74	78	70
Calcium, %	0.44	2.51	1.60	1.36
Phosphorus, %	0.22	1.01	0.70	0.54
Magnesium, %	0.10	0.42	0.26	0.21
Copper, ppm	15	130	183	92
Zinc, ppm	30	247	322	318
Iron, ppm	< 1,000	2441	1538	2051

Table 4. Plants and microorganisms used in the production of biomass from animal manures (adapted from Seal, 1992)

Biological agent	Process	Reference
Bacteria		
Thiopedia rosea	Chemical flocculation of anaerobic lagoon liquid	Freedman *et al.* (1983)
Thipedia rosea, *Thiocapsa* sp., *Chromatium* sp.	Biomass from swine manure	Earle *et al.* (1984)
Corynebacterium sp.	Fermentation of swine manure for lysine production	Sanders (1993)
Fungi		
Aspergillus niger	Biomass from swine manure	Brown *et al.* (1980)
Rhizopus sp.	Fermentation of swine manure	Taiganides *et al.* (1979)
Coprinus cinereus	Semi-solid fermentation of cattle and pig slurry with straw	Seal and Burrows (1981)
Algae		
Scenedesmus sp., Coelastrum sp.	High-rate algal pond with diluted swine manure	Groenweg *et al.* (1980)
Chlorella vulgaris, *Chlamidomonas* sp., *Ankistrodesmus* sp.	High-rate algal pond with diluted swine manure	Fallowfield and Garrett (1985)
Scenedesmus falcatus, S. quadricauda, *Chlorella* sp.	High-rate algal pond with separated and diluted pig slurry	Sevrin-Reyssac (1998)
Plants		
Duckweed	Duckweed ponds with diluted pig slurry/swine lagoon effluent	Culley and Epps (1973), Stanley and Madewell (1975), Bergmann *et al.* (1999)
Water hyacinth	Pilot-scale ponds with diluted pig slurry	Polprasert *et al.* (1991)

Table 5. Protein production by algae and other feedstuffs (adapted from Seal, 1992)

Source of protein	Protein yield (lb DM/acre-year)
Chlorella pyrenoidosa	14,000
Spirulina platensis	21,700
Clover	1,500
Grass	600
Wheat	270
Milk (cattle)	90

Biomass harvesting and the problem of breaking the hardly digestible cell walls are major obstacles in full applications of algal ponds. Algae can be harvested by a variety of separation technologies, including chemical flocculation, sedimentation, air flotation, centrifugation, and filtration. The cellulose and hemicellulose, which make up some 50% of the cell walls, are only partly digested by ruminants. The selection of appropriate strains may preclude some of the limitations such as poor digestibility, favorable temperature, and light conditions.

Hauck (1995) stated that the development of a high quality feedstuff from algae commensurate with the cost and degree of sophistication needed for acceptably pure algal production, harvest, and processing would be welcome. However, such complex and integrated schemes can only be economical if the end products are unique, meet special market needs, or can be produced more cheaply than other alternative products.

The use of defined cultures of bacteria and fungi in the production of biomass from animal manure has received less attention than the use of algae. The phototrophic purple sulfur bacteria have been investigated for their value in the treatment of swine manure to reduce concentrations of sulfide in anaerobic lagoons. These bacteria have been found to be suitable as feed for fish, zooplankton, and poultry. There have also been attempts to produce bacterial single cell protein from swine manure after aerobic treatment and solid separation. Koziarski and Oleszkiewicz (1980) attained 39% of crude protein in the dry matter content of chemically treated excess sludge from an activated sludge plant treating swine manure. The digestibility index (ratio between digestible protein and total protein) of the material was estimated to be about 60%.

Sanders (1993) studied the fermentative production of lysine using ammonia from pig manure as a raw material on a small pilot plant. Approximately 75% of the nitrogen-containing compounds present in the separated liquid phase are converted to lysine during the fermentation process.

The use of fungi has some advantages over bacteria in that they can be used in both semi-solid and liquid systems. Fermentation processes are used for the production of protein. Yields of 20–47% protein products have been reported using different species of fungi (e.g. *Aspergillus* and *Candida* sp.). Seals and Burrows (1981) reported on a process that strips ammonia from separated liquid fraction of pig slurry and passes it through wetted straw inoculated with *Coprinus cinereus*, a fungus indigenous to straw. The fungus grows on the ammonia by preferentially utilizing the hemicellulose fraction. The resultant straw had increased digestibility and enhanced protein content.

Duckweed (*Lemna* sp.) and water hyacinths (*Eichhornia* sp.) can rapidly cover the surface of ponds enriched with natural marsh effluent or nutrient-bearing wastewater. Both plants are fast-growing and prolific, with some *Lemna* sp. being capable of producing up to 22 tons/ac of high quality protein (high content of lysine and methionine) (Hauck, 1995). Polprasert *et al.* (1991) reported water hyacinths production of 2,700 lbs./day (70% moisture content) in pilot-scale ponds treating the liquid fraction of pig manure.

Harvested duckweeds have high nutrient content. They can be used as organic fertilizer (freshly harvested) and for composting. Dried or pelletized duckweeds have been used as a feed for fish, poultry and livestock. Polprasert *et al.* (1991) described experimental trials on composting and ensiling of water hyacinths. The end products could be used as supplemental feed to cattle.

Recent research on duckweeds has been focusing on the potential of different species as scavengers of nutrients from animal manures or as a high protein feed amendment. Bergmann *et al.* (1999) reports on nutrient removal from swine lagoon effluent using three different strains of duckweed. Nitrogen reductions between 70% and 90% were obtained using duckweeds grown on 50% and 25% diluted swine lagoon effluent. Phosphorus changes ranged from 30–60%. Other minerals are also removed from the lagoon effluent using duckweed.

Chemical recovery Of valuable nutrient compounds

Recovery of nitrogen compounds from animal manure depends on the manure characteristics. Most of the nitrogen-containing compounds are present as ammonium. Depending on the type and age of manure, part of these compounds may also be present as protein, amino acids, urea, and nitrogen-containing fiber material.

Rulkens *et al.* (1998) discuss potential possibilities, bottlenecks, and future technological challenges in recovering nitrogen compounds from agricultural liquid wastes. Several physico-chemical processes are aimed at recovery of ammonia from liquid manure. The end product can be an aqueous ammonia solution, or a mineral salt solution such as ammonium sulfate, ammonium phosphate, or ammonium nitrate. These products can be reused as fertilizers or for denoxification of exhaust gases from mechanically ventilated barns.

Table 6 summarizes some of the physico-chemical processes discussed by Rulkens *et al.* (1998) for the recovery of nitrogen compounds from swine manure.

Stripping and precipitation of nitrogen compounds from swine manure can be applied on a farm-scale. Precipitation of struvite (magnesium ammonium phosphate hexahydrate: MgNH4PO4.6H2O) for example, may be an interesting option for the farmer. Formation of struvite in flush water recycle pipes has been problematic in liquid manure handling systems because it can entirely block the pipes. Most published material on struvite deal with its removal and prevention in manure handling systems (e.g., Westerman *et al.*, 1985).

However, struvite has been found to be a good plant nutrient source for nitrogen and phosphorus since it has a slow releasing capacity and low solubility in water. Beal *et al.* (1999) have recently reported on the forced precipitation of struvite from anaerobically digested manure using magnesium oxide (MgO). Addition of 830ppm of MgO provided a 95% reduction in available phosphorus in the liquid. Concentrated excess phosphorus in the form

Table 6. Technological processes available for the recovery of nitrogen compounds from swine manure

Process	Applicability	Product	Use
Ammonia stripping and absorption	Raw slurry, separated liquid slurry	Aqueous ammonia solution, salt solutions	Fertilizer
Transmembrane chemo-sorption of ammonia	Separated liquid with no suspended and colloidal particles	Highly concentrated ammonium salt solution	Fertilizer
Precipitation of ammonium salts	Separated liquid (free of particles), raw slurry (???)	Aqueous ammonia solution, ammonium salt solutions, struvite	Fertilizer

of struvite could then be transported to phosphorus deficient cropping areas.

Conclusion

Currently either a low technological approach or a turn-key package will be the preferred options for the farmer who wants to recover nutrients and biomass from manure. Return of the nutrients to land is the most obvious option. Little or no effort has to be put into marketing and distribution of products. Processing manure for the production of biogas, compost, feed components or supplements from manure may require significant capital investment. Such an integrated system would be more appropriate for large units or cooperatives. Collection and distribution of manure and end products would be an important part of the financial equation. It must also be realized that manure processing and transport further increase fossil fuel consumption, particularly if drying is involved. The extra energy expenditure may offset any energy savings made by the adoption of a resource-recovery approach to manure management.

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