Beneficial Use of Swine By-Products: Opportunities for the Future

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Chapter 16

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The U.S. pork industry, like many other agricultural enterprises, is undergoing tremendous restructuring as production moves towards a greater degree of integration and specialization. Economic efficiencies related to the size of production facilities have led to a rapid centralization of the swine production industry that is still underway (Kliebenstein & Lawrence, 1995).

Swine production in the USA has historically revolved around relatively small and diversified farms. Pork production was primarily centered in the Corn Belt states because of the abundant supply of reasonably inexpensive feed. These farms typically followed the conventional pattern of grain and swine production, using locally produced feeds. The livestock manure, when returned to the land, provided an essential nutrient source for the grain production required to sustain the cycle. Pork producers typically had a complete farrow-to-finish operation, where animals were bred, born and raised to market weight on one farm.

American swine production is now in the midst of a trend toward fewer, larger, and more specialized farms (Fig. 16-1). For several reasons, there has been an increase in the size of the farms, vertical integration, and contract production (Lawrence et al., 1997). A study by McBride (1995) showed that both feed and labor efficiencies were significantly greater and death losses lower for hogs raised under contractual arrangements than for hogs produced independently. Polson and Hudson (1990) found that volume purchasing by swine producers leads to significant price discounts and that premiums are commonly paid for high-quality hogs when sold in a larger volume.

It is clear that swine production is rapidly becoming more specialized, concentrated, and industrialized, and these changes are expected to accelerate (Lawrence, 1992). In fact, Hayenga (1994) stated that large “integrated” hog production and packing operations by Seaboard Corporation, Smithfield, and Premium Standard Farms may be the tip of the iceberg of emerging structural change in the pork slaughter industry.

The segregation of pigs during various growth stages also has become a common practice. Separation by age allows feeding and nutritional programs to be op-
timized and housing conditions maintained appropriately to minimize animal stress. There are four primary types of swine operations. In feeder pig production, the producer maintains a breeding herd and produces "feeder" pigs for sale at an average weight of 20 kg. A feeder-to-finish farm will purchase feeder pigs and raise them.

Fig. 16–1. The farm size (number of swine raised per farm) responsible for swine production in Iowa (○) and North Carolina (◇) since 1974 (from the U.S. Dep. Commerce, 1994).
to slaughter weight (100–120 kg). On a farrow-to-finish farm, breeding and feeding to market weight are done on the same farm. Finally, a seedstock operation is devoted to the production and maintenance of breeding boars.

In some parts of the world there has been increasing public concern with swine-production practices that are perceived to be excessively confining for the animals. Concerns over animal welfare and housing conditions have led to legislation in certain European countries regulating swine housing conditions. For example, current regulations in Germany require that sows have at least 4 wk out of their stalls or crates during pregnancy. However this freedom of movement can make it more difficult for the farmer to monitor sow health and the progression of gestation. Regulations in the UK completely prohibit the use of sow stalls and tethers. Additional regulations on the swine-raising environment include rules on the type of ventilation systems, special accommodations for sick animals, proper lighting and adequate lying areas. Other concerns relative to animal welfare in the production of swine include tail docking, teeth clipping, castration, early weaning, and appropriate handling and transport. As this trend towards regulation of animal welfare increases, changes in housing and production practices will certainly influence the production and quality of swine manure by-products.

**SWINE MANURE PRODUCTION**

As with all domestic livestock, the overall retention of the nutrients consumed in feed by swine is relatively low. In general, at least 75% of the N, 80% of the P, and 85% of the K contained in swine feed is excreted. Swine urine comprises approximately 40% of the total weight of swine excrement and contains nearly 50% of the N, 4% of the P and 55% of the K. Clearly, management of nutrients from the urine fraction of swine excrement must be included as an important part of the overall nutrient handling strategy.

Unlike manure collected from grazing animals, the initial nutrient content of swine manure is relatively constant on farms with similar production methods. This is because swine are fed diets consisting primarily of corn (*Zea mays* L.), grain sorghum (*Sorghum vulgare* L.), and soybean (*Glycine max* Merrill) meal, with added minerals and vitamins. Any differences in the nutrient composition of manure largely can be attributed to variations in the method of collection, dilution, storage, or stage of animal growth.

Typical chemical and physical properties of swine manure have been well characterized in a number of reports (Table 16–1). However, the manure characteristics and the quantities generated also can be affected by specific animal factors (such as the size, breed, sex, level of activity), the environment (housing, temperature, humidity), and the diet (protein, digestibility, fiber content, amount of mineral supplements). Using "average" values for estimating the nutrient concentration of manure may be attractive due to occasional delays and costs associated with sampling and chemical analysis, however these assumptions can frequently be erroneous. For example, Payne (1986) found that the N concentration in swine manure ranged from 1.8 to 5.0% due to variations in feed composition. Similarly, Wilhelm et al. (1980) reported that the N concentration in three similarly operated
Table 16-1. Average manure production by swine excluding bedding. (adapted from Ensminger & Parker, 1984).†

<table>
<thead>
<tr>
<th>Production stage</th>
<th>Average weight kg</th>
<th>Daily manure production cm³</th>
<th>Annual manure production m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sow and litter</td>
<td>180</td>
<td>19,000</td>
<td>6.9</td>
</tr>
<tr>
<td>Prenursery pig</td>
<td>10</td>
<td>850</td>
<td>0.3</td>
</tr>
<tr>
<td>Nursery pig</td>
<td>25</td>
<td>2,000</td>
<td>0.7</td>
</tr>
<tr>
<td>Growing pig</td>
<td>55</td>
<td>4,000</td>
<td>1.5</td>
</tr>
<tr>
<td>Finishing pig</td>
<td>85</td>
<td>7,000</td>
<td>2.6</td>
</tr>
<tr>
<td>Gestating sow</td>
<td>150</td>
<td>5,700</td>
<td>2.1</td>
</tr>
<tr>
<td>Boar</td>
<td>180</td>
<td>7,000</td>
<td>2.6</td>
</tr>
</tbody>
</table>

† Includes solids and liquids, including additional 15% from waterers and washwater (average density of manure is 960 kg m⁻³).

Lagoons ranged from 309 to 938 mg N/L. Clanton et al. (1991) reported changes in swine manure characteristics as the animals were exposed to variations in environment and feed, as well as changes in animal size. Clearly, using “average” nutrient concentrations is not appropriate, given the range in nutrient composition found in manure, slurries, and effluent (Campbell et al., 1997). Progress has been made in estimating the N concentration and potential nutrient availability for plants from various organic materials, but these methods can not yet replace traditional laboratory analysis.

OUTDOOR PRODUCTION

Swine were once commonly raised in outdoor pasture situations. Although this practice is much less common that it once was, there may be situations where this production technique remains desirable. In moderate climates, for example, outdoor production has much lower start-up costs compared with specialized swine houses. Rotational grazing, gleaning of harvested fields, and specially planted crops for swine forage [e.g., clover (Trifolium species) and turnip (Brassica rapa L.)] are all useful practices for outdoor swine production. In some countries, the shift to outside swine herds is in response to new animal welfare laws that outlaw crates and tethers.

Although start-up and operational expenses are considerably less for outdoor swine production, economic factors such as depreciation rates and land requirements also must be considered (McGlone, 1996). Manure from outdoor-raised pigs is not easily recoverable and is spread nonuniformly over the land. This makes it difficult to use the manure for anything other than a plant nutrient source.

MANURE AND BY-PRODUCT TREATMENT

Much of the economic analysis of by-product treatment and utilization has viewed manure management as a factor separate from animal management. How-
ever, this short-term perspective does not properly reflect the complexity of modern livestock production. Since animal weight gain and manure are coproduced, there exists a feedback relationship between manure management decisions and manure production practices. For example, if the costs associated with manure management begin to significantly decrease the profit from animal rearing, overall production decisions should be altered to account for this.

The optimal combination of treatment and application technologies for an individual farm depends on the "value" of manure (Hoag & Roka, 1995). If the value of the swine manure is judged to be greater than potential treatment costs (e.g., as a fertilizer replacement), management options will be considered (Stonehouse & Narayanan, 1984; Honeyman, 1996) that might not be feasible where the net value of manure is deemed negative (Schnitkey & Miranda, 1993). When the "value" of manure is determined, the potential benefits need to be considered along with the costs incurred in transportation and application of the material. Treatment and transportation costs must be considered as part of the net value of manure. Additionally, the "nutrient value" of swine manure should only be calculated as the commercial fertilizer actually replaced and not merely the total value of all the nutrients contained in a given quantity of manure.

When making treatment decisions, the swine producer is faced with a complex set of multiple management options. The decisions regarding manure generation, treatment, storage, utilization, and land application all are integral parts of a successful and comprehensive swine production plan.

A number of techniques have been utilized for both the disposal and beneficial use of swine manure. Some examples include land application, methane gas
Table 16-2. Influence of swine house design and manure management systems on environment conditions (adapted from Smith, 1994).†

<table>
<thead>
<tr>
<th>Floor type</th>
<th>Relative space required</th>
<th>Temperature gradient</th>
<th>Pen shape constraints</th>
<th>Air quality</th>
<th>Pen hygiene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully slatted</td>
<td>100</td>
<td>No</td>
<td>No</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Part slatted</td>
<td>104</td>
<td>Yes</td>
<td>Yes</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Part scraped</td>
<td>104–120</td>
<td>Yes</td>
<td>Yes</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Deep bedded</td>
<td>245</td>
<td>Yes</td>
<td>No</td>
<td>Good</td>
<td>Moderate</td>
</tr>
<tr>
<td>Sloping</td>
<td>100–110</td>
<td>Yes</td>
<td>Yes</td>
<td>Good</td>
<td>Moderate</td>
</tr>
<tr>
<td>In situ composting</td>
<td>160</td>
<td>No</td>
<td>No</td>
<td>Good</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

† Extreme variations may occur due to day-to-day management on an individual farm.

(biogas) production, evaporation, NH₃ production, solid separation, hydrolysis, hydrogenation, composting, animal refeeding, and use as a substrate in plant and microbial protein synthesis (Fig. 16-2). The feasibility of any of these techniques varies considerably due to geographic location and economic considerations. Although many of these technologies are still in the testing phase, a combination of technologies may prove to be more suitable than any one alone. However as disposal costs escalate and regulations become more restrictive, a re-examination of alternative management practices and technologies will be necessary.

**MANURE HANDLING SYSTEMS**

Manure from swine farms are generally handled as either: (i) solid from bedded areas or drained floors, (ii) semiliquid or slurry from bare floors, or (iii) liquid from under slotted floors or runoff from under pens (Table 16-2). The composition and properties of the manure will vary according to the size of pig, the type of feed, the amount of bedding, and the manure handling system. Among domestic livestock, swine produce more manure per live weight than any other species (Ensminger & Parker, 1984).

The most appropriate treatment of swine by-products will vary depending on the objectives and resources of the individual producer. For example, treatment of swine manure may be carried out with the primary objectives of conservation of plant nutrients, reduction in nutrient load, minimization of odors, the reduction of solid accumulation in ponds, or some combination of these and other factors.

Decisions regarding a specific biological treatment and land application plan require many considerations beyond nutrient content. Treatment options may range from minimal (storage pit) to intensive composting. The by-product management plan should maximize economic and environmental benefits, while allowing the producer to remain in compliance with legal guidelines. Often the grower faces the choice between investing in treatment technology or acquiring sufficient land for manure application. Local constraints to land application frequently narrow the crop selection and also may require the purchase of additional field equipment. More intensive by-product treatment may allow higher application rates and reduce the amount of land needed for application, but incur greater processing expense.
TREATMENT FACILITIES

Ponds and Lagoons

Ponds or lagoons provide a relatively inexpensive and simple means of treating swine by-products on the farm with the objective of reducing the nutrient content and biological activity prior to subsequent application to land (Andreadakis, 1992). Lagoons typically contain large populations of microbes that thrive on the abundant supply of regularly added fresh organic matter. Swine lagoons are usually classified as either aerobic, facultative, or anaerobic depending on the $O_2$ status in the liquid. The dissolved $O_2$ concentration in the lagoon determines the microbial population in the liquid and the fate of added swine by-products. The concentrated swine manure that first enters the lagoon, or the first lagoon in a multistage system, generally causes the liquid to become anaerobic due to the high biochemical oxygen demand (BOD) of the incoming material. Anaerobic lagoons are popular because inefficient bacterial growth due to low concentrations of dissolved $O_2$ causes much of the organic matter to convert to methane. The methane and other organic gases diffuse from the lagoon liquid into the atmosphere and the $O_2$ demand is reduced 75 to 85%.

Anaerobic digestion is carried out by a diverse group of bacteria. A range of fermentative bacteria is responsible for the initial hydrolysis and fermentation of incoming organic materials, resulting in intermediary substrates such as succinate and lactate. During the next step (acetogenesis), acetate, $H_2$, and carbon dioxide are the primary by-products. The last step of anaerobic digestion results in methanogenesis (Marty, 1986).

Nitrogen is readily lost from anaerobic swine lagoons through $NH_3$ volatilization. It is estimated that as much as 50 to 75% of the N entering the lagoon may be subsequently lost via volatilization (Mikkelsen, 1997). This loss of N to the atmosphere greatly reduces the nutrient concentration of the lagoon liquid. Since most effluent applications to cropland are currently based on the N concentration of the liquid, N loss via volatilization allows a greater volume of liquid to be applied to a given area of land. From 15 to 30% of the excreted N is volatilized using storage pits compared with 70 to 95% volatilization losses using an anaerobic lagoon (MWPS, 1985). In situations where manure disposal issues are more pressing than nutrient conservation (for example with a limited land base accessible for application), using an anaerobic lagoon may encourage the volatilization of $NH_3$. The regional impacts of widespread $NH_3$ volatilization are not yet understood.

Anaerobic treatment lagoons do not facilitate regular P removal. A large fraction of the P entering the lagoon accumulates in sludge at the bottom of the pond. The P-containing sludge is generally removed from the lagoon at infrequent intervals (10–20 yr) and applied to surrounding land at rates to meet the N requirement of the crops. This practice results in an overapplication of P, as do most repeated applications of manure.

Aerobic Ponds

Manure treatment ponds can be maintained in an aerobic state by regularly pumping air into the liquid. Aeration helps minimize odors, nitrify much of the an-
monium, and stabilize organic materials via oxidation compared with anaerobic treatment. Although this technology is common in many municipal and industrial processes, it is not as common on swine farms due to the expense of continuously operating a mechanical aerator and complications associated with the process (CAST, 1995). However, significant reduction in odor and minimization of NH3 volatilization can be achieved through this practice. Aerobic treatment ponds generally result in greater production of microbial biomass compared with anaerobic lagoons.

**Multi-Stage Treatment Ponds**

A multistage system or series of lagoons can be used to combine some of the beneficial features of each type of treatment. For example, by-products may first enter an aerobic lagoon or subsection of a large lagoon for initial oxidation of organic matter, nitrification, and odor control. The liquid then passes to an anaerobic zone where the solid fraction is further treated and the nitrate removed through denitrification. This aerobic/anaerobic treatment process further reduces the N concentration in the liquid and allows a greater volume of liquid to be applied to a given area of cropland. Anaerobic lagoons are usually smaller than aerobic lagoons and decompose organic matter per unit of volume, but aerobic lagoons generally provide a higher degree of treatment with less odor production. A second lagoon also may provide valuable storage capacity for the treated liquid.

**Other Treatment Processes**

Treatment of liquid swine manure and deliberate loss of N can be similarly accomplished in sequencing batch reactors that utilize alternating aerobic and anaerobic conditions (Fernandes et al., 1991). Aerobic bioreactors also can achieve primary treatment of liquid swine manure prior to discharge of the final effluent for algae cultivation (Doyle & de la Noue, 1987). Aerated reactors using biofilm percolation systems for maintaining a trickle-type filter have been shown to accelerate initial nitrification and denitrification in liquid swine manure (Boiran et al., 1996). An additional approach is to use intermittent aeration in a single-activated sludge reactor in order to alternate between nitrification and denitrification (Liao et al., 1993). This approach resulted in a BOD reduction of between 92 and 98%, with a reduction in total N of between 59 to 70%.

There may be insufficient soluble C in the swine effluent following the nitrification step for optimal denitrification. Handbooks for wastewater treatment commonly suggest methanol as a source of C substrate in these situations (EPA, 1975), however, many soluble C sources have been used for this purpose. For example, molasses is effective at stimulating denitrification from swine effluent leaving a nitrification reactor (ten Have et al., 1994).

Methods of chemical precipitation of N and P from the swine liquid leaving digesters or lagoons prior to discharge have relied on additions of amendments such as alum [Al₂(SO₄)₃], hydrated lime [Ca(OH)₂] or zirconium tetrachloride (ZrCl₄) (e.g., Couture et al., 1988; Barrington & MacKenzie, 1989). Potential disadvantages of this approach to removing soluble nutrients from liquid swine manure involve
Table 16-3. The fraction of N, P and solids found in different size fractions in flushed swine manure (adapted from Hill & Tollner, 1980).

<table>
<thead>
<tr>
<th></th>
<th>Large particles (&gt;1.0 mm)</th>
<th>Medium particles (1.0-0.1 mm)</th>
<th>Small particles &amp; dissolved (&lt;0.1 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total solids</td>
<td>33</td>
<td>12</td>
<td>55</td>
</tr>
<tr>
<td>N</td>
<td>15</td>
<td>15</td>
<td>70</td>
</tr>
<tr>
<td>P</td>
<td>15</td>
<td>27</td>
<td>58</td>
</tr>
</tbody>
</table>

the subsequent disposal of the accumulated chemical sludge and the on-going cost of amendments.

**SOLID SEPARATORS**

Removal of swine manure solids from the farm waste stream is frequently the first step in allowing the material to be processed into more valuable products that can be marketed and used off the farm. However, many of the common techniques for concentrating swine manure solids do not result in a significant reduction in nutrient content due to the small-sized particles (<0.1-mm diam.) that are frequently not trapped, nor in significant odor reduction (Table 16-3). A combination of improved separation technology and higher demand for separated solids will help make this process more efficient. Several types of solid separators are currently used on a limited basis on swine farms.

**Screened Solid Separators**

A number of screen-type separators are available with various designs to remove swine manure solids. Perhaps the most common models involve a stationary inclined screen over which the manure and liquid pass. After separation, the solids are generally allowed to drain to minimize their volume and to become stackable (about 10% dry matter) while the liquid drains into a reservoir. The screens must be maintained periodically to prevent crusting and subsequent loss of efficiency.

**Centrifugal Separators**

Centrifugal separators remove the solids from the liquids by means of a perforated rotating cylinder that allows the passage of water, but retains the solids. This type of separator may remove more solids and reduce the moisture content more than the screen-type separator, but does not generally remove a significantly greater proportion of nutrients. They typically operate slower and with a higher energy demand than the screen-type separators.

**Other Separators**

Other techniques and equipment have been used with varying degrees of success to separate solids from swine manure slurries. Separators using presses, where
the manure passes between spring-loaded rubber rollers, have been successfully used. Belt presses also have been demonstrated to effectively remove liquid from swine manure slurries. Other solid separators operate using compression from hydraulically driven screws or rams to remove liquid from the wet manure. The economics and utility of these separators needs to be considered on a case-by-case basis with a clear end-use for the separated solids in mind.

Further removal of solids from wastewater can be accomplished with chemical flocculation or coagulation. For example, Sievers et al. (1994) reported that pH manipulation (pH > 9) was effective at promoting coagulation of swine wastewater. Additionally, they reported that several synthetic polymers and chitosan were effective at removing swine solids. Similarly, addition of small amounts of polyacrylamide to dilute wastewater results in much more efficient removal of suspended solids in mechanical separators (80%) compared with nontreated wastewater (5–20%) (Vanotti et al., 1999).

The use of membrane filters may someday be useful in separation of swine solids. For example, Bilstad et al. (1992) reported on a process in which anaerobically digested swine manure was first mechanically dewatered through a screw-type press. The resulting liquid fraction was then passed through a reverse osmosis membrane that removed 95% of the N from the liquid fraction. Polycarbonate, screen-type membranes also are effective in removing solids and microorganisms at varying pore sizes. Bobbitt and Betts (1992) reported that screen-type membranes can selectively remove bacteria from solution when the pore size of the membrane filter is progressively changed (0.22–12.0 μm). The feasibility of using membrane filters for nutrient, microbial, and solid separation of swine manure has not yet been demonstrated on a large scale.

**INDOOR MANURE STORAGE**

Many swine production facilities feature manure storage structures below slatted floors. The manure accumulates in a liquid form (approximately 10% solids) to allow handling and cleaning with water. Manure is commonly stored for 12 to 36 wk (3–9 mo) before clean-out and application to cropland where it is used as a source of plant nutrients. Aboveground prefabricated tanks also are commonly used to provide 12 to 48 wk (3–12 mo) of temporary storage. These aboveground tanks typically cost more per unit of storage capacity because of their stringent requirements for structural strength and the need for additional transfer equipment.

When manure is stored inside a building or tank, gases emitted from microbial processes may create a potentially hazardous environment and undesirable odors. Unless the manure is agitated and maintained in an aerobic state, anaerobic digestion results in the release of ≥40 different gases, many of which are toxic or irritating (Donham et al., 1977). Common gases produced during manure decomposition include H₂S, CH₄, NH₃, and CO₂. Potential human and animal health problems from the atmosphere within a swine facility include irritation of the eyes, mucous membranes, and the respiratory tract from H₂S and NH₃ (Donham et al., 1988). Acute toxic exposure to H₂S and explosions from CH₄ have been reported. Consequently, no one should enter a manure storage tank without proper precau-
tions such as adequate ventilation, nearby assistance, and proper breathing equipment. Fatalities regularly occur when these safety measures are overlooked.

Adequate ventilation of swine barns is the most effective way to eliminate harmful accumulation of gases from the manure, but ventilation rates are typically based on the need for cooling and moisture removal, not elimination of potentially harmful gases. Sutton et al. (1987) suggested that addition of water to the manure pit and frequent flushing can reduce NH3 concentrations in the swine barn atmosphere to concentrations that are not harmful to animals or workers.

**DISPOSAL OF TREATED LIQUID**

**Irrigation**

The decisions relative to the application of the liquid phase of treated swine manure onto surrounding cropland depend on the grower’s primary objectives and legal restrictions. Regulations in most regions stipulate that swine liquid may only be applied to an actively growing crop or applied immediately prior to planting a crop that will utilize the nutrients contained in the liquid (especially N). However, within these general guidelines, the liquid may be applied to either the smallest area possible (e.g., to minimize application or land costs), or over a larger area to maximize the efficiency of the nutrients.

The treated liquid may be applied to land using several techniques. Flood irrigation, fixed sprinklers, traveling irrigation systems, and center-pivot systems are all successfully used to apply dilute swine effluent to cropland. A variety of manure spreaders are commonly used to apply more concentrated slurries and manure to cropland.

Although swine manure is an excellent source of essential plant nutrients when added to cropland, little attention has been given to the minor chemical compounds present, some of which have been shown to be phytotoxic. For example, swine manure contains fatty acids that can significantly inhibit seed germination, with long-chained fatty acids being more toxic than short-chain acids (Edney & Rizvi, 1996). Other phytotoxic organic compounds (such as phenolic compounds) may persist in anaerobic conditions, yet are degraded relatively rapidly when stored in an aerobic environment (Ishaque et al., 1985)

**Evaporation**

As swine production expands into arid and semiarid regions, the use of evaporation ponds may become more common. This practice is most successful where evaporation greatly exceeds precipitation and where large areas of flat, relatively impermeable land are available. When designing an evaporation pond, it should be noted that water loss from the ponds will likely be less than published evaporation rates due to the formation of crusts on pond surfaces that act as a barrier to water loss. It may be advantageous to have a series of ponds, where the first pond serves as a solid-settling basin and subsequent ponds serving as evaporation ponds. This may minimize crusting problems and facilitate periodic removal of the sludge. With this management system, large evaporation ponds are flooded with 0.3 m of efflu-
Within a few weeks, the evaporation pond is generally dry and additional effluent can be added. After many months, the accumulated solids can be removed and added to cropland.

**USING MANURE AS A NUTRIENT SOURCE**

For centuries, the productivity of crops and grasslands has relied upon nutrient inputs from organic materials and animal manures. Therefore the historic value of swine manure has been primarily as a source of nutrients for crop production. However the availability of relatively inexpensive synthetic fertilizers during the past 50 yr, coupled with the increasing cost and labor associated with collecting, hauling, and spreading manure, has diminished its value as a nutrient source. As the swine industry moves towards further concentration of large animal operations within a geographic region, the limited agricultural land available for manure spreading adjacent to farms magnifies the limitations of using manure solely as a nutrient source (Barker & Zublena, 1996). Although primarily applied to land as a source of N, swine manure also effectively provides P, K, and other essential plant nutrients. There is abundant data to show the effectiveness of swine manure as a fertilizer source that will not be reviewed here (e.g., CAST, 1995). However, it is important to briefly address the factors that determine the value of swine manure as a nutrient source and certain management practices that should be considered.

The nutrient content of swine manure can be highly variable, which is not surprising considering the wide range in production practices and manure management strategies. Without knowledge of the nutrient concentration, it is impossible to manage manure in the most appropriate manner. There are no widely accepted methods for determining the nutrient content of manure on the farm.

The mineralization of nutrients from organic to inorganic forms also will impact the nutrient value of the swine manure. With swine manure treated in aerobic lagoons, the majority of the effluent-N is present as NH$_3$-N (>85%) and is readily available for plant uptake. However, when the manure is handled as a solid, a slurry, or when containing bedding material, much of the total N may still be present as organic N-containing compounds. Nitrogen mineralization rates are commonly estimated based on the properties of the by-product material and the anticipated soil environmental conditions following application, but this aspect of nutrient management is still not as precise as needed (Mikkelsen, 1996).

Volatile losses of NH$_3$ following application of swine manure to the soil can be significant. Nitrogen losses as high as 50% or more of the applied N via NH$_3$ volatilization are commonly observed following surface application of slurries and effluent. This volatilization loss will vary greatly depending on soil properties, environmental conditions, by-product characteristics, and application methods. Application techniques such as subsurface injection or plowing immediately after manure additions can virtually eliminate all volatile NH$_3$ loss. The addition of swine manure also may stimulate denitrification losses from the soil since large amounts of C, N, and water are simultaneously applied to the soil.

The use of swine manure as a N source for plant nutrition generally results in overapplication of other essential nutrients. An accumulation of P and trace el-
Table 16–4. Comparison of swine manure management in Iowa and North Carolina based on economic optimization (adapted from Roka, 1993).

<table>
<thead>
<tr>
<th></th>
<th>Iowa</th>
<th>North Carolina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary receiver crop</td>
<td>Corn</td>
<td>Bermuda grass</td>
</tr>
<tr>
<td>Production environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop yield</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Manure value</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Climate</td>
<td>Cool</td>
<td>Warm</td>
</tr>
<tr>
<td>Treatment costs</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Management systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N losses</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Level of treatment</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Transportation method</td>
<td>Haul slurry</td>
<td>Irrigate from lagoons</td>
</tr>
</tbody>
</table>

...elements (e.g., Zn and Cu) typically occurs with repeated swine manure applications (Mikkelsen, 1995). This build-up occurs as the application of nutrients exceeds the quantity removed in harvested crops, drainage, and surface losses. The site-specific characteristics of a field and the soil buffering capacity will determine the environmental impact of this long-term accumulation. The potential negative effects of this nutrient build-up on soil and water quality, plant nutrition, and grazing animals are not well known.

The value of swine manure as a nutrient source to replace commercial fertilizers is clearly evident for farms that grow crops and have adequate land for application. However, for swine farms not involved in crop production or farms that do not have livestock for grazing, the economic value of swine manure, relative to commercial fertilizers, is more difficult to measure. In a comparison of swine production in Iowa and North Carolina, Roka (1993) reported that North Carolina producers have relatively low crop yields, therefore they have a low “perceived” value of manure and aim for low treatment costs. A different situation exists for Iowa swine producers who use minimal treatment and apply the manure to corn, a crop that brings higher economic returns than bermudagrass (*Cynodon dactylon* L. Pers.) (Table 16–4). The conditions in these two states clearly offer differing incentives for managing manure-derived nutrients.

Swine manure application rates must be adjusted according to the agronomic requirements of the crop and the site-specific characteristics of the field (Mikkelsen & Gilliam, 1995). Crop yields may be depressed by excessive rates of manure application. Elevated nutrient concentrations in groundwater also can result from inappropriate application. Overapplication of manure can possibly result in harmful concentrations of nitrate in forage crops, as well as grass tetany, fescue toxicity, and fat necrosis.

Sainsbury (1983) reported that application of manure slurry could be a mechanism for spreading harmful organisms onto soil and pastures. This practice is especially associated with *Salmonella* and *Escherichia coli*, but Sainsbury also suggests that other organisms such as *Bacillus anthracis*, *Mycobacterium tuberculosis*, *Clostridia* spp., and *Leptospira* spp. also could survive in manure slurry. It has been found that salmonella infection can be spread onto soil through slurry and that active organisms can survive in slurry for at least 12 wk (3 mo) (West, 1976). Like-
wise, pig manure has been noted as a source of trichonomiasis in cattle, caused by the protozoan parasite *Trichomonas suis*. The presence of active swine enteroviruses also may influence the use of swine manure products. Derbyshire et al. (1986) reported the highest viral frequency in raw manure, with decreasing frequency observed as the degree of anaerobic digestion increased. However, they regularly detected the presence of swine enteroviruses in manure samples, regardless of the degree of anaerobic processing.

**ODOR MANAGEMENT**

One major limitation to improved utilization of swine manure is the objectionable and distinctive odor. Odor from swine manure results from a complex mixture of gases including organic acids and volatile N-based and S-based compounds. Considerable effort is underway to evaluate various amendments that can be added to the manure to reduce odor release. For example, Zhu et al. (1997) reported on five odor-control additives that were effective in reducing odor from stored swine manure. Several of the additives also were effective in reducing the concentration of volatile fatty acids.

An alternative approach to reducing odor emissions is to modify the swine diet. For example Farnworth (1995) reported that addition of a small amount of Jerusalem artichoke (*Helianthus tuberosus* L.) to swine diets made a noticeable improvement in the smell of the swine manure. Other feed additives that influence the microbial population in the swine digestive tract also might result in improvements in odor problems.

As an alternative to additives (such as chemicals and enzymes) for odor control, researchers have shown that air scrubbers and air filters can be effective at removing particulate matter and odor from swine-production facilities. Other odor management options include covering the surface of the stored manure with crop residues or low density floating material to form a physical barrier that seals the surface from the atmosphere, or installation of wet pad scrubbers and microbial biofilters.

Odor complaints also may arise during land application of the manure. Complaints following slurry application are reduced when the manure is injected beneath the soil surface instead of spread on the surface. Injecting the manure also results in conservation of much of the N that would otherwise be volatilized from the soil surface. Odor from irrigated effluent also may be objectionable in some conditions. The planting of windbreaks to divert airflow away from neighbors may prove valuable for odor control.

**DIET MANIPULATION**

It is possible to change the nutrient characteristics of swine manure by modifying the diet (Honeyman, 1993). Much of the P present in the grain components of swine feed is indigestible. Phosphorus digestibility of feeds by swine ranges from 25 to 35% for soybean meal to only 10% for maize (Cromwell, 1990, Ravindran,
As much as 60 to 70% of the total P in grains is present as indigestible phytic acid compounds (inositol). This phytate can only be utilized for animal nutrition following enzymatic hydrolysis, dependent on the activity of phytase enzymes. In monoruminant animals, such as swine and poultry, this enzyme is not present, or present only in small quantities. As a result, a growing pig on typical feed rations will excrete more than 60% of the P in the feed and a breeding sow will excrete more than 85%. Given the poor utilization of P in grains, the traditional approach for supplying adequate P is to supplement feed with a source of inorganic P, such as dicalcium phosphate.

There is increasing concern about the enrichment of soils and waters resulting from overapplication of P to soils from animal manures. For example, when swine effluent is used as a N fertilizer source for bermudagrass hay, 2.5 to 3 times more P is applied to the crop than is removed in the harvested crop. One approach to reducing P excretion by swine is to add phytase enzymes to the feed, which allows the pigs to digest at least 30% more P in the grain (Coelho & Kornegay, 1996). Less P mineral supplement is then required for nutritional purposes and less P is excreted in the manure. The addition of phytase also has been shown to increase digestion and utilization of other essential minerals, such as Cu, Ca, Mg, and Zn (Davies & Nightingale, 1975).

Another approach to reducing P excretion in swine manure is to use feed grains that are already low in phytic acid. There are currently experimental varieties of corn available that have as much as 60% less phytic acid than traditional varieties (Raboy & Erbasi, 1996). Growth and feed digestibility of swine fed this low phytic acid corn appear to be satisfactory (Spencer et al., 1998).

It may be possible to minimize N excretion by adjusting feed rations to reduce the protein content of swine feed to more closely meet the precise nutritional requirements. When the protein content in swine feed is lowered by 1%, the N excretion is reduced by approximately 10% (Evans, 1995). In the USA, it is common to feed a “grower” diet (30–60 kg wt) and a “finisher” diet (60–100 kg). By increasing this to as many as three or four different diets precisely adjusted for the stage of growth, it may be possible to further reduce nutrient excretion (Lenis, 1989). However, in lowering the overall protein content of the feed, it may be necessary to supplement the feed with synthetic amino acids (such as lysine, methionine, threonine, and tryptophan) to maintain growth. Several commercial blends of synthetic amino acids and enzymes are currently available as feed enhancers. This approach would require a higher degree of management and multiphase ration adjustment as the nutritional needs of the growing pigs change. The economics of such an approach towards feed manipulation also would have to be considered and compared with other options of handling the manure-derived N.

**SWINE BY-PRODUCT UTILIZATION**

Future developments in swine by-product processing include better utilization of these products as a resource. Enhanced utilization may include combinations of wet oxidation, electrophoresis, enzyme technology or anaerobic water treatment. Solid by-products generated from these various technologies may be used as
a source of nutrients, soil conditioners, or possibly for industrial purposes. The solid
fraction of swine manure may be best suited for separation of specific amino acids
and proteins, or substrate for algae fed to animals and fish. Perhaps manure could
be used as a raw material for production of NH₃, ammonium phosphate, carbon dioxi-
dide, fats, and oils. However, each of these products has its own established market
and these processed manure derivatives would face stiff economic competition. An
additional obstacle to increased use of refining/separation technology may be the
difficulty in removing ingredients such as antibiotics, disinfectants, and trace met-
als from swine manure. The variable chemical and physical properties of swine man-
ure will likely pose a challenge for processing also. Some of the more promising
uses for swine manure are presented here.

**MANURE AS A FEED SUPPLEMENT**

As more swine are raised in confinement, there will be more opportunities
to beneficially reuse by-products on the farm. Refeeding swine manure solids to
other animals is one practice that will potentially increase the utilization of feed-
derived nutrients and improve overall feed conversion efficiency. Less is known
about the refeeding of swine manure than with poultry or cattle manure. Addition-
ally, the majority of the studies on refeeding swine manure have been relatively
short term in duration. Recycling swine manure as a feed source also raises ques-
tions about animal health. However, concerns regarding potentially pathogenic bac-
teria from properly processed by-products do not appear to be significant (e.g., Mc-
Caskey & Wang, 1985).

Refeeding of swine manure is generally done following separation of the solid
fraction from the liquid. Dry matter digestibility of swine manure fed to swine was
reported to be 50%, while the amino acid digestibility ranged from 51 to 65% (Ko-
regnay et al., 1977). When dried swine manure was substituted in cattle diets, the
dry matter digestibility was reported to be 31%. There are numerous examples of
reefing processed swine manure on an experimental basis, but there has not yet
been widespread adoption of this practice.

Swine manure has a relatively high water content and tends to degrade
rapidly when stored. The high costs of drying swine manure have led to the ex-
ploration of other processing options for converting swine by-products into feed.
Mixing solid swine manure with a cellulosic material to produce silage has been
shown to be an attractive possibility (Berger et al., 1981). For example, ensiling wet
swine manure with other feed materials appears to be feasible for producing high-
quality feed (Iniguez-Covarrubias et al., 1994). During the ensiling process (lactic
acid fermentation), large reservoirs of fecal coliform bacteria, pathogenic Salmon-
nella, and other dysentery organisms are killed. Ensiled swine manure also is a good
source of P and Mg for animals (Cooke & Fontenot, 1990).

Various treatment processes also can enhance the feed value of swine manure.
For example, treating the manure with a solution of NaOH will break down some
cellulose and lignin, allowing microorganisms to convert more of this material into
nutritionally useful compounds (Flachowsky et al., 1990).
The use of feed additives to enhance the health and growth of swine is quite common in intensive swine production. However, as the additives appear in the manure, they may potentially alter the processing of swine manure due to their antibacterial properties. For example, the addition of dimetridazole to swine feed enhances swine growth and prevents hemorrhagic enteritis (being active against anaerobic bacteria). After ingestion it is rapidly eliminated from the pig, primarily in the urine. However, Fougerat et al. (1987) reported that biogas production from swine manure may be either enhanced or inhibited by the presence of dimetridazole, depending on the concentration. Other antibiotics (such as avilamycin) do not appear to have detrimental effects on anaerobic digestion of swine manure (Sutton et al., 1989), but little is known about the impact of many of these additives and their fate when feeding by-products to other animals.

It appears that swine manure can be an important and nutritionally valuable component in animal diets. Using swine manure as an animal feed offers a promising method to conserve nutrients and energy-rich resources, while reducing potential pollution problems. Recycling this low-cost feed ingredient can possibly reduce animal production expenses as well. However, this practice should only be initiated after careful consideration of the presence of potentially harmful factors such as detrimental microorganisms, residual additives, and the possible presence of relatively high concentrations of trace metals. Similarly, the health of the animals and humans consuming the animal products should be carefully considered.

**BIOGAS PRODUCTION**

During the anaerobic decomposition of swine manure, natural microbial processes result in production of methane (biogas). There is considerable potential for energy production from farm manures as a result of anaerobic digestion when organic matter decomposition is managed for this purpose. On-farm digesters produce a mixture of gases [composed primarily of methane (> 60%), carbon dioxide, water vapor, and other trace gases], which may be suitable for use in heating, lighting, and other energy-intensive applications. Anaerobic digestion also reduces the BOD and chemical oxygen demand (COD) of the manure. During the digestion process, the readily decomposable organic materials are microbially degraded and the remaining solids are more homogeneous than the raw manure.

Swine manure is a relatively good substrate for use in biogas generation, compared with other animal manure. Approximately 500 to 600 L gas/kg may be produced from swine manure solids. Fresh manure is much more biodegradable than aged or dried manure because of the substantial loss of volatile solids from manures with time. Yang et al. (1993) reported on the development of a small treatment plant for swine wastewater that reduced volatile solids while producing methane. A variety of systems have been designed to accommodate larger amounts of swine and other animal manures (U.S. DOE, 1995).

There are significant problems with biogas production from swine manure that have limited its widespread adoption as a beneficial-use process. For example, there can be considerable capital costs associated with the initial construction and subsequent operation of a biogas generator. It was estimated that a minimum
swine herd size of between 3000 and 4000 was required before farm collection of methane was economically justified (DOE, 1995). Additionally, after the raw swine manure has been digested, the remaining solids must still be handled and disposed of appropriately. The biogas production process requires considerable skill to operate efficiently and is subject to inhibitory processes that may interfere with biogas generation.

Methane generation is more rapid at mesophilic temperatures and some digesters may need to be heated to >35°C and the contents regularly mixed for optimal gas production. The water content of the manure used for biogas generation is critical. Therefore, a solid separator may need to be used in order to keep the digester feedstock at a relatively consistent moisture content. Elevated concentrations of metals (e.g., Cu) added to swine feed may inhibit anaerobic digestion. Since high concentrations of NH₃ present during the digestion process can inhibit biogas production, some processing may be required to eliminate this constituent. Although both BOD and COD are significantly reduced following the digestion process, further treatment of the liquid is still required prior to discharge into surface water. A good overview of the potentials and limitations of agricultural generation of biogas is given by Ross and Walsh (1996).

Many of the biogas generators built during the 1970s and 1980s were of the plug flow reactor design, optimally operated in the mesophilic range (20–45°C). More recently, attention has been placed on the use of covered anaerobic lagoons for biogas recovery. These systems have the advantage of simplicity in design and operation. However, these systems are most efficient in the psychrophilic temperature range (<20°C), making biogas production very susceptible to temperature fluctuations (Saflley & Westerman, 1989). The production of biogas from normally operated anaerobic lagoon does not appear to be sufficiently consistent to be a reliable source of energy (Saflley & Westerman, 1988).

When considering production of biogas and the marketing of the residual solid fraction, the current economic situation must be carefully evaluated and compared with other treatment options before beginning such an operation. The fluctuations of world energy prices can rapidly change the economic feasibility of this practice (Durand et al., 1987).

Biogas methane is potentially dangerous and highly explosive. Being heavier than air, it will displace O₂ in confined spaces and can therefore pose a respiratory risk to humans and animals. The storage of more than a few days output is prohibitively expensive, therefore the gas must be used as it is produced, perhaps to power an electrical generator. A considerable commitment of time and resources is required to successfully operate a biogas facility from an anaerobic digester.

Ahring et al. (1992) proposed the treatment of animal manures in combination with organic industrial wastes and household solid wastes to produce biogas and organic fertilizers. They suggested that this multifeedstock approach may be more feasible than focusing on the utilization of a single organic substrate, although this increases transportation costs. To be successful, it is likely that a large-scale biogas generation must have a constant supply of raw material, the methane must be utilized as it is generated, the effluent must be utilized or further treated, and the remaining solid fraction should be used as a value-added product.
Although energy production is one potentially beneficial result of controlled anaerobic digestion, parasite and pathogenic bacterial counts also are reduced by more than 90% through this process (Fenach et al., 1983). Pain et al. (1990) reported that anaerobic digestion of swine manure slurries reduced odor emission by between 70 and 74% compared with the undigested manure. Reducing NH₃ concentrations in an anaerobic digester has a dual function. Since the production of biogas is optimized as NH₃ concentrations are kept low, the NH₃ can be used to produce ammonium phosphate fertilizer solution by passing the NH₃-containing air through phosphoric acid.

**COMPOSTING**

One option for treatment of swine manure is compost production. Composting swine solids involves thermophilic processing and decomposition by aerobic microorganisms to produce a relatively stable organic material (Lau et al., 1992). Composting has been successfully conducted with varying levels of technology on farms of all sizes, however the more sophisticated approaches can require considerable effort and expertise to operate effectively. Swine farms with smaller numbers of animals may effectively use a simple composting system, such as a static windrow. For large-scale operations or where high-quality compost is desired, some mechanical composting system may be more appropriate (Haywood, 1997).

When swine manure is removed from the barns using water and handled as a liquid, it is too wet and dilute to be directly composted. With a wet-manure handling system, the dilute effluent/slurry from the barns can be processed through a solid separator and the solid fraction used for composting. The solid fraction from the mechanical separation is rich in fiber and moisture and may be well suited for composting. However, separation of manure solids is not a common practice on most farms, so the immediate potential for widespread composting of swine manure solids is not great. Research has been conducted on composting “liquid” manures and this technique has been successful in degrading some solids and controlling odors from the swine manure (Woods, 1980).

Although there is considerable interest in composting, there are not many operations that compost swine solids on a large scale. Solid swine manure alone (without further processing or composting) has an offensive odor and physical properties are not conducive for direct horticultural uses. However, combining the swine manure with a high-C bulking agent prior to composting will improve aeration and the physical properties of the manure, resulting in excellent quality compost. During the composting process, temperatures generally exceed 55°C and many of the odorous S-based gases (such as H₂S, methylmercaptan, and methyl sulfides) are rapidly removed from the maturing compost (Fig. 16–3). It is important to maintain a well-aerated environment during composting, since these malodorous compounds are primarily formed and emitted under anaerobic conditions. Pathogens and parasites present in manure are generally killed or inactivated at elevated composting temperatures. Another advantage of composting is the reduction in volume that occurs during the process. Much of the C is respired as the microbes degrade...
the organic material, reducing the volume by up to 50% during the composting process.

Kuroda et al. (1996) studied the production of compost from swine feces composted with cardboard fragments. They reported a 60% reduction in weight and 30% loss of total N during the composting process. Volatile fatty acids, initially at high concentrations, were rapidly reduced during the first few hours of composting. This is significant since volatile fatty acids are frequently considered to be a major source of offensive odors in fresh swine feces. However, during the composting process, the emission of NH₃ and volatile S compounds continued to be the major sources of odor (Tanaka et al., 1991).

The addition of mineral acids to swine manure for treatment can reduce gaseous losses of NH₃; however Derikx et al. (1994) found that upon drying, acidification also increases losses of volatile fatty acids. Therefore, steps taken to reduce one volatile substance (e.g., NH₃) may increase the volatility of another. Since many volatile compounds are responsible for manure odor, the overall effect of these management practices during the composting process is complex.

There are many reports of successfully composting swine manure solids with various bulking agents. For example, Lo et al. (1993) reported that a 5:1 ratio of swine manure solids and sawdust formed the substrate for excellent compost. Gonzalez et al. (1992) had good agronomic results from a compost initially composed of 80% swine manure solids, 10% clay, and 10% other animal manures. Piccinini et al. (1995) produced a high-quality compost from a mixture of separated swine solids, straw, and wood chips. They also reported an elevated concentration of Cu and Zn in the compost, originating from the solid fraction of the separated swine manure. Georgacakis et al. (1996) found that incorporating ground lignite with the swine manure-based compost resulted in a superior final product than that

\[ \text{Fig. 16-3. Changes in concentrations of volatile S compounds during the composting of swine manure (adapted from Harada et al., 1993).} \]
not receiving lignite, due to improvements in physical properties and a reduction in odors.

The high concentrations of Cu and Zn present in some swine manures are a potential cause for concern in composting. Repeated use of composts that are enriched in trace metals can result in rapid build-up in soil (Mikkelsen, 2000). The concentration of metals is not regulated in animal manure-based composts at this time, but this issue will need to be addressed as this practice becomes more widespread.

One innovative producer in Virginia replaced a traditional windrow-based composting system for cattle manure with pig-based composting by allowing the manure and bedding from a 50-cow herd in an open-sided shed to accumulate during for 90 to 100 d during the winter (Shirley, 1994). Following the occasional addition of straw, wood chips and grain, the cattle are again turned out to pasture in the spring. A small herd of pigs root for food in the accumulated organic material, thereby turning and aerating the pile and producing a compost for subsequent on-farm use.

VERMICOMPOSTING

It has long been known that earthworms are important in decomposition of organic manures and residues. Although several earthworm species have been evaluated for their potential in processing organic materials, the most studied species include *Eisenia fetida*, *Eudrilus eugeniae*, *Perionyx excavatus*, and *Dendrobaena veneta*. Swine manure can be an excellent medium for worms, however the excess water should be separated from the solid manure fraction in slurry or effluent before use on worm beds. Additionally, since fresh swine manure may contain high concentrations of salt and NH₃, a period of composting or leaching may be required prior to application directly to worms (Chan & Griffiths, 1988). Swine manure also may contain a relatively high concentration of trace metals that may be injurious to earthworms (Edwards, 1988). After addition to worm beds, it is important that the swine manure not undergo the heating process normally associated with composting, in order to avoid damaging the worms.

The vermicomposting of dewatered swine manure is currently being on a farm that conducts the entire process within an enclosed greenhouse facility (Riggle, 1997). The finished product is odor-free and extremely consistent throughout the year, since the composition of the manure does not change during the year and extreme environmental fluctuations are eliminated by the use of the greenhouse (Mikkelsen, 1999).

When the processing of the swine manure is complete, the resulting product (vermicompost) is a peatlike material that has excellent physical properties for plant growth (Dominguez et al., 1997). The nutrient composition of the vermicompost will depend on the swine manure initially used, but swine manure-derived vermicompost provides a range of essential plant nutrients.

Results from numerous greenhouse experiments show that plant growth in vermicompost may equal or exceed plant growth in conventional peat-based growth media (Handreck, 1986, Edwards, 1988). In addition to the desirable physical and nutritional properties, there is indication that other plant growth-enhancing prop-
erties may result from fertilization with vermicomposted organic materials. For example, Tomati et al. (1988) observed a positive plant growth response that they attributed to a hormonal effect in the vermicompost. They speculated that this resulted from microorganisms present during the vermicomposting process, since it is known that some microorganisms are capable of producing plant growth hormones.

Following separation of the vermicompost from the worms, the use of worms as animal feed has been suggested. Worms are rich in minerals, vitamins, niacin, and provide an unusually good source of vitamin B12 (Edwards, 1998). In small-scale studies, earthworm protein has been successfully used for feeding fish, chickens, and swine. However, the high value of earthworms generally precludes these uses.

More information is clearly needed on the potential of worm-based processing and the proper use of the resulting vermicompost. The optimization of the entire process needs evaluation as well as examination of potential markets for the finished material.

CONSTRUCTED WETLANDS

The liquid fraction of swine manure or the liquid remaining following solid separation still contains a relatively high nutrient concentration, as well as high BOD and COD. This effluent requires further treatment or management prior to discharge to surface water. One technique that has been investigated is use of constructed wetlands for the treatment of wastewater as it flows slowly through a series of ponds or cells. Many species of aquatic plants have been investigated for use in wetland-based treatment, but common reed (Phragmites australis Cav. Trin. Ex Steudel) has been the focus of the most research.

This reed species has stiff aerial shoots with both horizontal rhizomes and normal roots. It has been effective in wastewater treatment since it is able to conduct O2 from the aerial portion of the plant through the stems and rhizomes into the rhizosphere. The large population of microorganisms that are supported on the root surface are effective at water treatment. This microbial activity can result in a significant reduction in BOD, COD, and NH4 in the passing water.

PRODUCTION OF MICROBIAL PRODUCTS

Swine by-products can be used beneficially for production of nontraditional "crops", such as bacteria grown in aerobic or oxidized treatment facilities. Bacteria, used as a single-celled protein source, can be periodically harvested, processed, and used as a food source for animals.

Several reports have been published detailing the potential for concurrent microalgae production and treatment of swine manure. For example, Noue and Basseres (1989) found that in addition to small Chlorophyceae, the cyanobacteria Phormidium bohneri was effective at removing over 90% of the organic N and inorganic P from anaerobic swine effluent. Similarly, Cañizares et al. (1993, 1994)
reported that immobilized cells of *Spirulina maxima* were effective at removing over 80% of the NH₄ and 90% of the total P from a diluted swine manure slurry.

Some blue-green algae (e.g., *Spirulina platensis*) have been used as a human food source in Africa for thousands of years. Algae grown in swine effluent could conceivably be used as sources of fats and oils, polysaccharides, and for animal protein (Moulton et al., 1980). Regions with warm temperatures and sunny skies will have the best success with algae production.

Filtered swine effluent has been successfully used in the production of green and blue-green algae for aquaculture, where the algae was utilized as the primary food source for cultured shrimp and fish. Behrends et al. (1980) reported that swine manure made an excellent fertilizer for fish production. Teichert-Coddington et al. (1990) found that excellent fish growth could be expected following addition of swine manure to ponds, but that careful management was required to sustain high levels of fish production. Integrated swine and fish production has been utilized quite successfully in China where agricultural land is limited and highly populated.

**STRUVITE PRODUCTION**

During anaerobic treatment of swine wastewater, various ions (e.g., NH₄, Mg, and PO₄) are released into solution. When these ions become supersaturated, magnesium ammonium phosphate hexahydrate (MgNH₄PO₄·6H₂O), commonly known as struvite, precipitates and forms "scales" that will clog pipes and pumps, thereby reducing their hydraulic capacity. Safley et al. (1982) reported that struvite formation can cause a serious problem in swine manure treatment systems using recycled flush water. The accumulation of struvite may become so extensive that it causes a complete failure of the treatment system.

Struvite precipitation in anaerobic manure treatment facilities typically occurs within the pipe network where pressure changes occur (e.g., at bends and inlets) and the inlet/outlets to settling areas. It has been hypothesized that a reduction in the partial pressure of CO₂ at these points may trigger struvite formation (Loewenthal et al., 1994). Considerable work has been done to understand the thermodynamics and the management practices responsible for struvite formation in order to prevent its occurrence (e.g., Wrigley et al., 1992; Buchanan et al., 1994a). Other work has been done to develop chemical treatment practices that inhibit struvite formation (e.g., Buchanan et al., 1994b).

It is feasible that the chemical properties of the swine manure liquid and the environmental conditions could be manipulated to promote struvite precipitation and subsequent collection. A major advantage of this technique for removing both N and P from the wastewater is that a valuable slow-release fertilizer is formed. Although this approach has been examined on a research scale (e.g., Wrigley et al., 1992; Webb & Ho, 1992; Liao et al., 1995), there have been no commercial attempts to produce struvite from anaerobic swine effluent.

Struvite is only slightly soluble in water (log K = 13.15) and has been previously used as a slow-release fertilizer in crop production. Its use as a fertilizer may be particularly advantageous when soluble fertilizers are inefficient, low soluble salts are required in the root zone, or when a long residual effect is required. For
example, Bridger et al. (1962) reported that increasing the particle size of struvite extends the nutrient release rate. Improved growth of grass, fruit, and various high-value crops was observed when fertilized with struvite, compared with conventional soluble fertilizers (Rothbaum & Rohde, 1976).

INTEGRATED ON-FARM MANAGEMENT

An award-winning swine operation in northeastern China is a good example of integrated uses of swine manure on a farm. Rinse water, used to clean the floors and remove the manure from the pigpens, is flushed into lagoons to fertilize water hyacinth. These lagoons cover 3.3 ha and produce 2500 Mg of hyacinth/yr. The hyacinth is used during the winter and spring as animal fodder. The water flows from the hyacinth lagoons into pools containing algae and azolla at the surface, with fish and crabs beneath. The azolla is periodically removed and used as a summer fodder source for farm animals. The water flows from this second pool into a third pool containing fish, crabs, and freshwater mussels. From this third pool, the water and remaining dissolved nutrients are used to irrigate and fertilize adjacent rice (Oryza sativa L.) fields. When the water leaves the rice field, it is sufficiently clean to be used again for rinsing the swine houses and begin the cycle again (Xinyan & Xiangyen, 1996).

A similar approach was evaluated by Noue et al. (1994) on a swine farm in France. Swine manure was diluted and processed through a sequence of ponds, the first of which was aerated and inoculated with Scenedesmus quadricauda and S. falcatus (for treatment and algae production for feed). The effluent then passed to a second pond that was inoculated with Daphnia magna, and then passed to a fish pond containing carp (Cyprinus carpio). The fish pond effluent was then returned to the algal ponds to dilute the swine manure. The ponds were all designed to produce biomass, which is harvested and used for various purposes. The operators of this integrated facility reported that additional work was still required to optimize the individual components of the complex treatment process. Additionally, cold winter weather resulted in the loss of treatment capacity for nearly 80 d when the water temperature was <5°C. Clearly, this type of integrated approach requires a high-degree of management and skill to successfully maintain manure and wastewater treatment year round.

MANURE BROKERAGE

Where a regional surplus of manure-derived nutrients occurs, one option is to export the manure to farms outside the region for land application. When this is necessary, it is advantageous to minimize the moisture content to reduce transportation costs and to stabilize the nutrients. Increasing the nutrient content with inorganic fertilizer sources and pelletizing the manure for easy handling may improve the attractiveness for potential users.

Innovative systems of manure brokerage have been used to encourage transportation of swine manure out from regions of excess nutrients to geographic areas that have a greater need for this resource. These attempts have typically depended on government subsidies to achieve economical stability and match manure gen-
erators with potential consumers, but economists estimate that this practice may be profitable under certain circumstances (Govindasamy & Cochran, 1995).

**CENTRALIZED “PROCESSING”**

A number of centralized processing strategies have been proposed for transforming swine manure into a dry, odorless solid that would have value for consumers. This approach has the advantage of allowing more expensive processing techniques to be utilized by pooling manure resources from a larger region, although greater transportation costs may be incurred.

A major difficulty in centralized treatment and processing of swine manure is the high water content (>90%), therefore treatment typically begins with separation of the dry matter from the water. Extraction of the water usually requires an input of energy. To reduce processing expenses and enhance the probability of overall success, energy costs and chemical inputs (such as acids or flocculents) must be kept to a minimum. An additional difficulty to processing is that pig manure is inherently a complex and variable material, containing at least 75 different recognizable chemical compounds in the organic fraction, salts, acids, proteins, fats, and minerals (Schurink, 1991).

In order to be successful, a centralized treatment process for swine manure should ideally incorporate the following considerations: (i) provide for recovery of products that can be reused, (ii) result in production of energy or require a minimal input of energy in processing, (iii) require a minimum input of chemicals, (iv) minimize the escape of potentially undesirable gases to the atmosphere, and (v) minimize environmental impacts during the treatment process.

A variety of innovative processes have been proposed for handling and treating swine manure (Table 16-5). For example, a processing plant using an evaporative technique coupled to steam cleaners is under investigation in France (Vel, 1996). This plant is capable of treating 380 L/h of swine slurry and produces a dry, easily handled product. Many such processing techniques have been proposed but only a few have advanced beyond the pilot plant stage. In general, the capital and operating costs of a central treatment facility have generally exceeded the market value of the products produced. The extent of potential markets for processed swine derivatives and the financial constraints associated with these markets also must be addressed early in the planning. Perhaps consideration of diminished environmental impacts that result from expanding into alternative treatment practices (beyond land application) and further restrictive regulations will change the economic constraints in the future.

Two centralized swine manure treatment systems have been utilized in Holland (Rulkens & ten Have, 1994). The “Promest” system involves initial anaerobic digestion of the swine slurry, followed by centrifugation. The resulting solid fraction is dried and pelleted, while the liquid fraction is further processed with aerobic treatment. The finished solid material has been shown to be a very effective source of plant nutrients (van Erp & van Dijk, 1992). The “Mennon” involves initial acidification to reduce NH$_3$ volatilization, followed by treatment with a biodegradable carrier oil with a high boiling point (such as paraffin oil) to allow dewatering of the manure. The swine solids are removed from the carrier oil and
### Table 16-5. Potential treatment processes for handling and treating of swine manure (adapted from Ruikens & ten Have, 1994).

<table>
<thead>
<tr>
<th>Process Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Concentration of colloidal and suspended particles</td>
</tr>
<tr>
<td>Filtration</td>
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<tr>
<td>Centrifugation</td>
</tr>
<tr>
<td>II. Removal, concentration or conversion of organic materials</td>
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<tr>
<td>Mechanical separation of suspended particles</td>
</tr>
<tr>
<td>Anaerobic digestion (with biogas production)</td>
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<tr>
<td>Aerobic treatment</td>
</tr>
<tr>
<td>Wet oxidation</td>
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<tr>
<td>III. Removal, conversion, or immobilization of N compounds</td>
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<tr>
<td>Volatilization and trapping in acid</td>
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<tr>
<td>Nitrification</td>
</tr>
<tr>
<td>Denitrification</td>
</tr>
<tr>
<td>Acidification with acids</td>
</tr>
<tr>
<td>IV. Removal of P compounds</td>
</tr>
<tr>
<td>Filtration and separation of colloidal compounds</td>
</tr>
<tr>
<td>Precipitation of soluble compounds</td>
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<tr>
<td>V. Removal or concentration of minerals</td>
</tr>
<tr>
<td>Evaporation and concentration</td>
</tr>
<tr>
<td>Reverse osmosis</td>
</tr>
<tr>
<td>VI. Treatment of manure solids from the filtration or reverse osmosis process</td>
</tr>
<tr>
<td>Drying</td>
</tr>
<tr>
<td>Incineration for energy production</td>
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<tr>
<td>VII. Treatment of exhaust gases produced during drying process</td>
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<tr>
<td>Dust removal</td>
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<tr>
<td>Bioscrubbing</td>
</tr>
<tr>
<td>Biofiltration</td>
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<tr>
<td>Incineration</td>
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<tr>
<td>VIII. Other treatment steps</td>
</tr>
<tr>
<td>Algae biomass conversion</td>
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<tr>
<td>Production of amino acids</td>
</tr>
<tr>
<td>Freeze concentration to remove water</td>
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<tr>
<td>Catalytic incineration</td>
</tr>
</tbody>
</table>

pelletized prior to sale. The carrier oil is separated from the water and the organic materials before being recycled again through the process.

The long-term success of such large-scale, centralized manure treatment facilities remains to be proven and substantial economic and technological hurdles remain. This centralized approach to treatment must compete with other manure-management options, such as transporting manure to other regions. The quantity of manure that could be processed by a large treatment facility is not known, therefore the feasibility of spreading the costs over a large number of farms is uncertain. Similarly, the potential income that could be derived from the sale of finished products is not clear. It is likely that centralized manure treatment plants will only be utilized after all other feasible options have been exhausted.

### REFERENCES


