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Increasing the Value of Animal Manure for Farmers

Teng Lim, Ray Massey, Laura McCann, Timothy Canter, Seabrook Omura, Cammy Willett, Alice Roach, Nigel Key, and Laura Dodson

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Abstract

Animal manure provides crop nutrients and improves soil quality. However, manure's nutrient variability and low phosphorus and nitrogen content per unit weight reduce its market value relative to chemical fertilizers. While manure remains an important source of fertilizer in many farming systems, alternative uses are becoming important. Manure can be used to generate renewable energy in the forms of heat, gas, and electricity with further processing, but innovation is required to compete against other renewable and nonrenewable energy sources. Entrepreneurs are also developing markets for fiber found in manure. Environmental policies related to animal farms, meant to protect air and water quality, can both raise manure management costs and increase manure's value as an energy precursor. This study uses data from the USDA Agricultural Resource Management Survey (ARMS) to describe current manure production, handling, storage, and use. An extensive literature review of manure-related research describes existing and emerging technologies that have the potential to increase the value of manure or reduce manure management costs. The study identifies potential government programs and policies for promoting the adoption of technologies that enhance manure value for farmers.

Keywords: Animal manure, livestock, crop nutrients, soil quality, fertilizer, renewable energy, environmental policies, manure management, liquid-solids separation, composting, anaerobic digesters, manure fiber, technology cost sharing, nutrient trading programs

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Contents

Errata

On August 18, 2023, barley acres planted data were corrected in table 2, which also impacted the acres of barley that were manured and the shares of manure-receiving crops data. No other data were affected.

USDA Economic Research Service
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A report summary from the Economic Research Service March 2023

Increasing the Value of Animal Manure for Farmers

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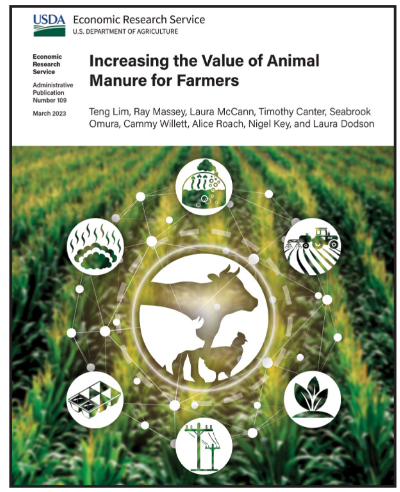
What Is the Issue?



Livestock production tends to be geographically concentrated in the United States, and in certain regions, animals generate more manure-supplied nutrients than are needed by nearby cropland. Manure has a low and variable nutrient density, making it costly to transport and apply to fields that are located far from animal production facilities. In addition, nitrogen and phosphorus levels in manures may not match the nutrient needs of crops. Inappropriately managing manure can impair air and water quality.

Developing new uses and markets for manure may result in both economic and environmental benefits.

What Did the Study Find?

There is substantial opportunity for increasing the use of manure as fertilizer. Manure was applied to only about 8 percent of the 237.7 million acres planted to 7 major U.S. field crops. Manure is a major source of crop nutrients in organic food production, which represents an expanding market in the United States. However, if manure-supplied nutrients exceed crop needs, crop producers will not demand the excess nutrients, lowering their value. Three hundred seventy-one counties in the United States have been identified as having more manure-supplied nutrients than crops need.

The fertilizer value of manure depends on the type of animal manure produced, how manure is stored and applied to land, and the cropping system to which manure is applied. The study identified several existing and emerging technologies for increasing fertilizer manure value. These include:

- Liquid-solids separation technologies create a solids component, which is more valuable and marketable as a fertilizer.
- Manure additives (such as nitrogen, alum, acid, biochar, and clay) can better match manure nutrients with crop needs, minimize negative environmental off-field impacts, and save time and cost in application.

- Composting manure—with or without animal bedding and other organic matter—reduces its volume, increases its value, kills weed seeds and pathogens, and reduces the potential for air and water pollution. USDA Agricultural Resource Management Survey (ARMS) data indicate that only 4 percent of manure-fertilized farmland received composted manure.

Manure has uses (other than fertilizer) that can create value for farmers. Processes to exploit potential non-fertilizer uses of manure that are identified in the report include:

- Anaerobic digestion can produce renewable energy (primarily methane) and turn manure and other organic wastes into a more consistent and sterile product.

- Thermochemical processes—such as pyrolysis (heating without air), gasification and combustion—yield fuel gases at a much faster rate than anaerobic digestion.

- Manure fiber can be transformed into livestock bedding and biodegradable containers for horticultural uses.

Governmental programs and policies can influence farmers' manure management decisions—with implications for farm profits, the environment, and public health. The study identified several possible ways to promote the adoption of value-added manure technologies, including:

- Technology cost sharing. Programs such as the USDA Environmental Quality Incentives Program could lower the cost of targeted manure technologies for farmers.

- Grants from governmental agencies and organizations. Research indicates that grants increased the adoption of new manure technologies.

- Co-op formation. Programs may incentivize co-op formation for participation in multi-farm digester systems and other value-added manure economic opportunities.

- Voluntary nutrient trading programs. Modifications to voluntary nutrient trading programs could increase incentives for livestock producers to participate.

- Increased Federal support for research and development could lower manure technology costs over time, enabling adoption by smaller farms. A systems approach to the research may facilitate the development of new technologies that benefit both farmers and the environment.

How Was the Study Conducted?

This report uses data from the annual ARMS—including the Soybeans (2018), Corn (2016), Oats (2015), Wheat (2017), and Cotton (2019) Phase II surveys to characterize current manure management and use. To characterize manure nutrient supply and demand, the report relied on recently published research on manuresheds.

The study synthesizes an extensive literature on manure-related research and summarizes the latest information on manure management and promising technological developments. The study also incorporates information from industry websites and commodity magazines about the most recent innovations in manure management. Information from conversations with various businesses is also incorporated to provide industry perspectives on emerging technologies and programs.

Increasing the Value of Animal Manure for Farmers

Introduction

The study considers the feasibility and practicality of emerging manure technologies; provides insight into what research and development opportunities are likely to provide the highest return; and characterizes developing technologies by stage of readiness. In accordance with the directive, the study focuses on farmers' economic incentives for manure technology adoption and use and considers environmental issues only as they relate to producer decision-making. While beyond the scope of this report, it is well-recognized that poorly managed manure can contribute to water quality problems such as eutrophication and the presence of veterinary pharmaceuticals, as well as air quality problems such as odor and greenhouse gas emissions (Waldrip et al., 2019).

The first part of this report presents an overview of the current state of manure production, handling, storage, and use in the United States and reviews Federal policy that influences manure management decisions. Data from USDA Agricultural Resource Management Surveys are used to quantify current manure use on crops, including manure nutrient application rates, animal sources of manure, manure market involvement, and application methods. This section of the report updates information provided in an earlier report on manure use for fertilizer and energy (MacDonald et al., 2009). The report also draws on recently published research about manuresheds to characterize the regional availability of manure nutrient supply and demand. This research integrates the 2012 Census of Agriculture data with crop nutrient use estimates from the International Plant Nutrition Institute and methodology and manure excretion estimates from the USDA Natural Resources Conservation Service.

The second part of the report describes technologies and practices available to increase manure-related economic opportunities for farmers, based on an extensive literature review and conversations with industry experts. The analysis provides the latest knowledge on how manure is being managed and on developments that offer promise for better using manure as a resource.

The third part of the report identifies potential Federal programs and policies for promoting adoption of technologies to enhance manure value for farmers, as well as potentially fruitful areas for Federally-funded research.

The Value of Manure to Farmers

For generations, farmers have used animal manure to fertilize their crops (Stevenson et al., 1926). In traditional agricultural systems, grazing animals deposit manure on pasture and cropland, effectively recycling many of the nutrients the animal consumed. In recent decades, producers have become increasingly specialized in either crop or livestock production, and livestock production has moved from pasture-based to primarily concentrated feeding operations (MacDonald et al., 2018). Commercial fertilizers developed in the past century serve as convenient, consistent nutrient sources and widespread adoption of commercial fertilizer facilitated this specialization in crop production (Hergert et al., 2015).

As production systems evolved, farmers increasingly adopted animal confinement systems, which led to manure production being concentrated in one location. A confined facility's manure has fertilizer value when it is spread on fields, but manure is costly to transport and spread. In some regions, confinement has resulted in the local supply of manure nutrients exceeding the nutrient needs of crops (Paudel et al., 2004).

Manure is a valuable source of nitrogen, phosphorus, and potassium, which can make it a substitute for, or complement to, commercial fertilizers. Manure also supplies a wide variety of micronutrients, including calcium, magnesium, and sulfur (Schott and Schmidt, 2017). In addition, manure provides organic matter and carbon, which makes manure a useful soil amendment for improving soil health, measured by chemical, physical, and biological properties:

- **Chemical:** Manure has been shown to benefit soil chemical properties by increasing soil organic carbon content, increasing nutrient retention and availability, and providing essential micronutrients. The specific benefits realized from amending soils with manure, however, depend highly on the manure's chemical properties (Schott and Schmidt, 2017).

- **Physical:** Manure has been shown to improve soil physical properties, including decreased bulk density, increased soil porosity, increased aggregate stability, and increased infiltration rates. These physical improvements affect how crops can access air, water, and dissolved nutrients in the soil, and they affect how well soils can resist degradation due to erosion and runoff (Schott and Schmidt, 2017).

- **Biological:** Although less research has focused on how manure applications affect soil biology, current work indicates that soils amended with manure have greater numbers of soil bacteria, fungi, and earthworms than soils amended with commercial fertilizers. Furthermore, compared with soil receiving commercial fertilizers, manure-amended soils show increased microbial activity, which indicates healthy nutrient cycling in the soil (Schott and Schmidt, 2017).

As discussed later in the report, because of its fiber content, manure also has promising value as a renewable replacement for horticultural peat and as bedding for animals. Manure can also be a valuable feedstock for energy production.

While manure has substantial potential value as a fertilizer to farmers, two characteristics of manure increase the costs of using it as a fertilizer replacement (Massey and Gedikoglu, 2021). First, manure has a low nutrient value-to-mass ratio. This is partly due to some manures' water content, which can be up to 90 percent of total weight. The low quantity of nutrients per ton, relative to commercial fertilizers, results in time-intensive and costly transportation. Depending on the weather, in any year, farmers may have a few days with suitable conditions that allow them to prepare fields, spread fertilizer, and plant. Crop planting takes priority, so to save time, farmers may choose commercial fertilizers rather than manure.

Second, manure as excreted and after storage has a nitrogen-to-phosphorus ratio that does not align with most crops' nutrient requirements. Applying enough manure to meet nitrogen needs may create environmental hazards due to high levels of phosphorus that accumulate in soil. This imbalance means that farmers apply supplemental commercial fertilizer to meet a crop's nitrogen needs instead of applying more manure. The nitrogen in manure is also susceptible to being volatilized into the air during collection and long-term storage before land application. Nitrogen volatilization further exacerbates the nutrient imbalance and can lead to health and environmental issues (Aillery et al., 2005).

A Framework for Evaluation

A central objective of this report is to better understand how to increase the value of manure for farmers. Farmers ultimately make their decisions about how they manage manure based on their farms' previous investments, land and labor resources, production system—and the broader technological, economic, and policy context. With this broad systems approach in mind, we have identified three themes that shape the potential for a given technology to enhance manure's value for farms: manure value versus cost, farm size, and adoption barriers. We use these three themes to discuss an optimum value model, or how farmers can optimize the value of their manure resource. The second part of this report discusses how these themes are likely to influence the viability and adoption of new technologies and practices.

Manure Benefits Versus Costs

Manure provides value from its ability to serve as a fertilizer or an input into energy production, animal bedding, or industrial processes. Incorporating manure into any product or process entails costs. The objective is to find a use for manure such that the benefits exceed the costs, i.e., that manure is profitable. When the cost of using manure exceeds the value derived from manure, farmers have several options:

1. Reduce manure management costs;
2. increase manure's value;
3. subsidize the loss from manure management with profits from animal production (e.g., consider manure a necessary cost, and internalize its cost into the animal production cost);
4. move to another location with lower manure management costs or greater manure value; or
5. stop producing altogether.

Opportunities to increase manure's value include transferring it to other locations where it has greater value or transforming it into other products. Adding value to manure may involve stacking multiple manure management benefits. Stacking already occurs in cases where producers receive income from selling manure-generated energy and renewable energy credits. As discussed in later sections, selling renewable energy might also allow producers to earn emission reduction credits that further increase net income.

To reduce manure's costs and increase its value, farms can make simple management changes or significant system changes. In some cases, farmers may treat manure management as a necessary cost to bear because they lack suitable technology or are operating in a location that is not conducive to manure use. Manure storage systems and application equipment choice can affect both value and cost. Moving to a different location can change the location-specific cropping systems, topographies, and climates that affect the opportunity for farms to capture value from manure.

Farm Size and Investment Costs

High initial fixed investment costs can result in economies of scale—larger farms can spread costs over more output, which reduces per unit costs and improves profitability. High fixed cost technologies may, therefore, be economical for large farms but not for smaller ones. High initial investment may also favor farmers who are able to self-finance because banks may be less willing to lend money for new or unproven technologies. Fixed costs associated with technology adoption and the resulting minimum efficient scale can result in barriers to entry and increasing scale of production (Martin, 1993). Economies of scale in swine and poultry production have resulted in cost advantages for large production facilities and are related to the rise of contracting in these industries (Martinez and Zering, 2004). Fixed costs may determine which types of technology will be adopted by specific types of farms.

Adoption Barriers or Drivers

Social scientists have examined the factors that affect adoption of new technologies by farmers since the 1950s. Mansfield (1961), examining adoption of industrial technologies, found that it was related to both profitability and the size of the investment. The development of new crop varieties in the 1960s and 70s led to further research as summarized by Feder et al. (1985). More recently, there have also been many studies on factors that promote adoption of conservation practices as summarized in Prokopy et al. (2019) and adoption of best management practices for manure such as Gillespie et al. (2010) and Gedikoglu and McCann (2012).

A robust finding is that the cumulative adoption level, as a function of time, is an S-shaped curve. Sunding and Zilberman (2001) explained that the shape is not due to the spread of information but variations in profitability among farmers, the threshold model. As an example, it may be profitable for some large farmers to adopt (termed early adopters) and, as the cost of the technology decreases, it becomes profitable for more farmers. Thus, characteristics of the technology, as well as the farms, play a role. Other research has found that characteristics of the farmer also may either promote or hinder adoption (see reviews by Pannell et al., 2006; Prokopy et al., 2019). While it should be noted that factors that promote adoption can be reframed as barriers, for simplicity, the discussion below relates primarily to drivers of adoption.

In addition to the profit, or benefit-cost considerations, social scientists have identified several factors that influence farmers' adoption of new technologies. These factors can be framed as barriers or drivers and include:

- **Complexity:** Less complex technologies are more likely to be adopted. Practices that save time and labor are more likely to be adopted, all else being equal (Rogers, 2003).

- **Trialability:** If farmers can try a technology with little risk or investment, such as planting a new crop variety, then they are more likely to adopt the technology (Pannell et al., 2006). For technologies with large upfront investments, this is not the case.

- **Observability:** Another factor shown to affect technology adoption is whether the impacts are observable (McCann et al., 2015). As an example, farms may be better positioned to track productivity metrics (e.g., yield and return on investment) than nutrient management's effects on water.

- **Operator demographics and attitudes:** Research has shown demographic factors such as age, income, and education can affect technology adoption as can the operator's attitudes toward risk (Pannell et al., 2012). Younger farmers and those with higher incomes and education levels are typically more likely to adopt. Education may affect how farmers find and use information as awareness of new technologies is a necessary but not sufficient condition for adoption. Uncertainty about technology may also be a barrier.

- **Environmental attitudes:** Farmers with stewardship ethics or those who feel concerned about environmental quality are more likely to adopt practices that have environmental benefits (Prokopy et al., 2019).

- **Market structure:** Farmers who are under contract with integrators—a typical arrangement for U.S. hog and poultry production—are responsible for manure management. However, most efficiency gains seen in hog and poultry production are due to technical change promoted by the integrators. This market structure, where many different stakeholders are involved in manure management decisions, may reduce incentives for technical change in manure management (McCann et al., 2005). Sneeringer and Key (2011) found that contracting increases regulatory avoidance by hog farmers.

- **Government programs:** Regulation can either induce or stifle innovation by firms, affecting their compliance costs. Government financial assistance programs, such as subsidies or tax credits, can increase adoption likelihood for technologies that are not privately profitable but are expected to benefit society. Governments may have multiple goals, such as farmer incomes and environmental impacts. Economic theory suggests that multiple instruments may be required to accomplish multiple objectives (Tinbergen, 1952) and interactions among policy instruments need to be considered (Capano and Howlett, 2020), including among instruments relating to manure (Abdo and Ackrill, 2021).

As an example of these concepts, Cowley and Brorsen (2018) examined the barriers or hurdles to U.S. dairy and swine producers adopting anaerobic digesters. Adopters indicated that greater adoption could be encouraged by lower construction costs, increased government grants, and higher electricity prices. Nonadopters indicated they didn't adopt because the costs exceeded the benefits, partly because the operations were too small to make the digesters cost-effective. To encourage more widespread adoption, these farmers suggested designing anaerobic digestion systems for small farms. The authors found that the decision to adopt digesters was mainly a function of government policies and economic factors, but other factors, including producer attitudes toward the environment, affected whether farmers even considered the technology. Abdo and Ackrill (2021), using both surveys and interviews, found similar barriers to adoption of anaerobic digesters in the United Kingdom and examined how the policy environment affects those barriers.

An Overview of Manure Production, Management, and Regulation

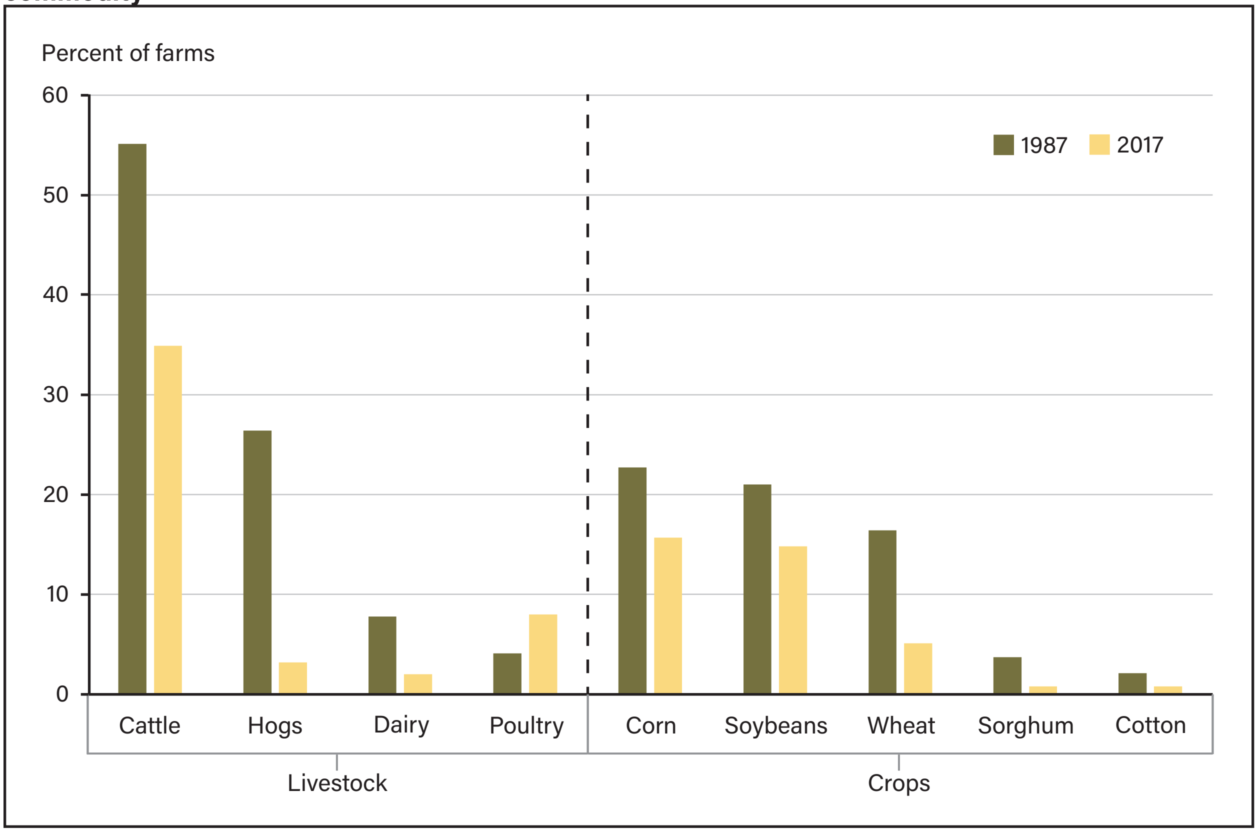
Decisions made by farmers, industry personnel, and regulators influence not only the cost of manure use but also the value of manure and manure's environmental impacts. In this section, we describe the current situation for U.S. manure production and use, and we highlight how regulators and policymakers have influenced how farms use manure and incentivized certain manure management practices.

Manure Production

Farming practices that geographically concentrate animal production can increase pollution risk (O'Donoghue et al., 2011) as the manure produced in a region can contain more nutrients than the locally produced crops can use. For example, economic factors have fostered animal production in some areas where crops are not common (e.g., poultry production in the Ozarks of Arkansas and Missouri) or where environmental concerns pose an issue (e.g., dairy and poultry in the Chesapeake Bay watershed). Structural change and location decisions are due to technological changes, economic factors, as well as public policy including regulatory stringency (Abdalla et al., 1995). Abdalla and his co-authors (1995) indicated that contracting has facilitated the clustering of livestock farms near centralized processing facilities.

Increasing farm size and specialization have changed manure handling and use and exacerbated the manure distribution problem. As farms have become more specialized, they have also increased in size and separated animal and crop production. Crop and animal farming specialization has occurred over the past century and especially since World War II. Farms specialized as they had access to mechanization and chemicals for fertilizer, pest management, and animal health (MacDonald, 2020). As a smaller number of commodities were produced on each farm, the share of all farms that produced any one commodity declined. Figure 1 shows this trend (between 1984 and 2017) for some select commodities. Specialization makes production more efficient by concentrating resources to their best use. However, specialization also segments activities that can be complementary.

Figure 1
Specialization as evidenced by the percent of all farms that produce a particular agricultural commodity



Note: Figure shows the percent of all farms producing the commodity and how it changed from 1987 to 2017.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, 1987 and 2017 Census of Agriculture.

The USDA estimates midpoint acreages and animal numbers for various farm enterprises. The midpoint is the point where half of all cropland or animals (for farms that produce that product) is on larger farms and half is on smaller farms. These estimates show the extent to which production has concentrated on larger farms over the last several decades. Between 1987 and 2017, the midpoint data show crop acreage increased from 166 to 243 percent, and animal numbers increased from 141 percent for fed cattle to 4,175 percent for hogs and pigs (table 1) (MacDonald, 2020).

Table 1
Midpoints of animal (head) and crop (acres) commodities

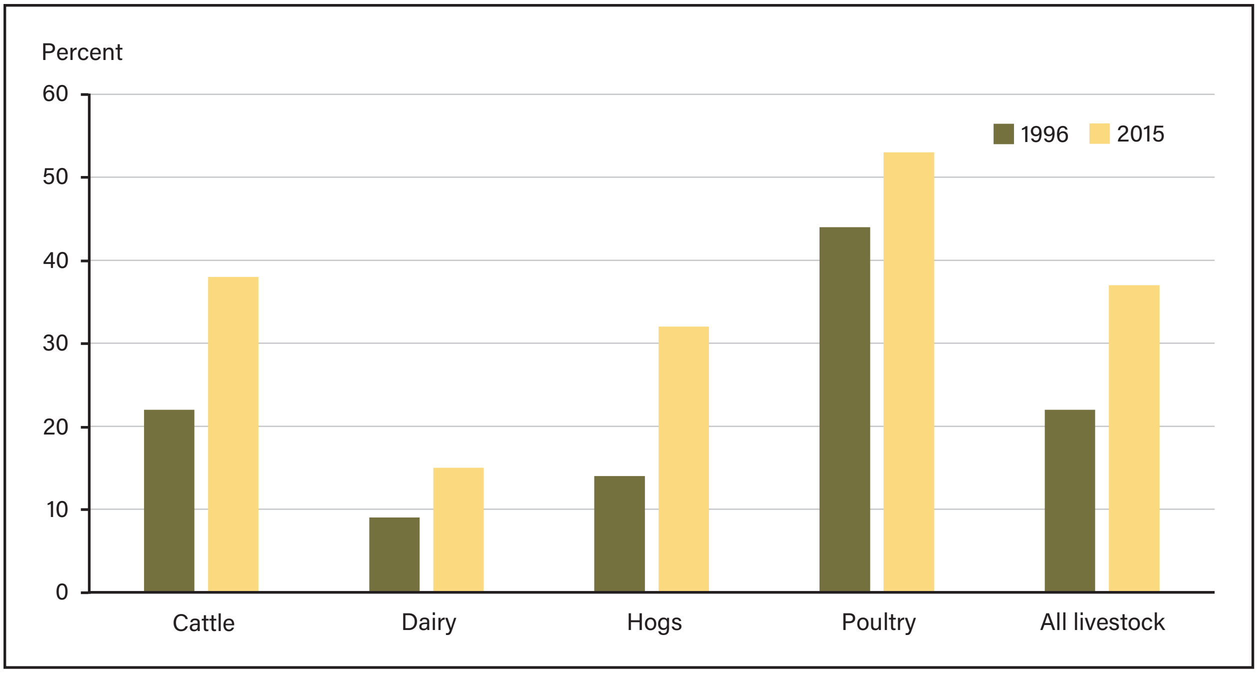
Commodity	1987	2017	Percent change
Crops			
Corn (acres)	200	685	243
Cotton (acres)	450	1,385	208
Rice (acres)	295	900	205
Soybeans (acres)	243	700	188
Wheat (acres)	404	1,073	166
Animals			
Broilers (number sold)	300,000	744,000	148
Fed cattle (number sold)	17,532	42,300	141
Hogs and pigs (number sold)	1,200	51,300	4,175
Egg layers (number in inventory)	117,839	1,200,000	918
Milk cows (number in inventory)	80	1,300	1,525

Note: Midpoint is the farm size where half of all cropland or animals are on larger farms and half are on smaller farms (for farms that produce that product).

Source: USDA, Economic Research Service using data compiled from USDA, National Agricultural Statistics Service, 1987 and 2017 Censuses of Agriculture.

An increasing share of animal producers grow no crops (figure 2). Therefore, these farms have no crops to benefit from the manure they generate. In some instances, animal-producing, manure-generating regions are now separate from crop-producing regions that could use manure as a nutrient source.

Figure 2
Percent of livestock production occurring on farms producing no crops



Note: Figure shows the percent of all livestock production occurring on farms with no crop production.

Source: USDA, National Agricultural Statistics Service and Economic Research Service, 1996 and 2015 Agricultural Resource Management Survey.

Dairy

Before modern refrigeration, dairy cattle were raised near population centers to sell perishable dairy products for local demand. Grain was transported to the dairies, forage was grown on the farm, and milk was transported to nearby processors. As refrigerated transportation became more available, the "dairy crescent" from New York through Minnesota emerged as the nation's dairy belt because forage crops had a comparative advantage over grain crops in the region's cooler climate, shorter growing season, and thinner soils (Peterson, 2002).

As milk supply grew beyond regional fluid demand in areas such as Wisconsin, cheese and butter processing industries developed, which had previously been located in the Northeast (Lewthwaite, 1964). In 1938, Wisconsin and Minnesota led the United States in milk production, and 90 percent of Minnesota farms had some dairy production (Koller and Jesness, 1940).

Rural electrification and adoption of automated milking equipment in the 1950's allowed many diversified farming operations to grow into specialized dairy farms. Larger dairy farms emerged where dairy had a competitive advantage. Milk pricing peculiarities, influenced by Federal dairy policy that had set higher prices for fluid milk produced further from Wisconsin since the 1930's (Fallert, 1981), also fostered expansion of dairies beyond the "dairy crescent."

Dairies in California grew to supply that State's rapidly expanding population after World War II. California was well-suited for dairies due to irrigated alfalfa supply, availability of low-cost byproduct feeds from the State's horticultural crops, and the availability of immigrant farm laborers. Water prices in the western United States are subsidized by the Federal Bureau of Reclamation, which lowers the cost of producing alfalfa, a water-intensive crop used mainly for dairy cattle in California (Konyar and Knapp, 1990).

Pioneered in California, the large-scale desert dairy model moved to other arid states in the West (Arizona, New Mexico, Idaho, Kansas, and Colorado), where the dry climate makes heat stress and environmental challenges easier to mitigate (Peterson, 2002). Improved milk quality meant longer shelf life for milk, and expanded interstate highways allowed dairies to locate further away from population or processing centers.

Dairies can collect animal waste as solid manure or slurry manure, or they can separate the manure into solid and liquid fractions. A lactating dairy cow excretes almost 18 gallons of fresh manure daily (ASABE, 2019). Because dairy manure contains a lot of water, short transportation distances make it more feasible to recover value from the manure.

Dairy farms produce substantial amounts of manure, which they can potentially use as fertilizer. A 500-head dairy using pit manure collected from a freestall barn would produce 5.3 million gallons of slurry manure each year. The manure would contain approximately 48 tons of plant-available nitrogen[1] and 40 tons of recoverable P_2O_5—a form of phosphorus (Lorimor et al., 2000). The manure would meet all the phosphorus needs of 1,435 acres of corn silage, yielding 18 tons per acre. Additional commercial fertilizer would need to be applied to meet the corn silage crop's nitrogen needs. The manure's value—due to its nitrogen, phosphorus, and potassium content—would be about $107,000 per year.[2] If manure were applied to meet corn silage's nitrogen needs, only 543 acres would be needed, but the manure's value would decrease to $71,000 per year. This value does not account for the cost of manure storage or application or any environmental impacts associated with the application of manure phosphorous at levels above crop requirements.

[1] Plant-available nitrogen is the fraction of excreted nitrogen that is available for crop use. Losses during storage and land application are not included. Excreted nitrogen is greater than plant-available nitrogen.

[2] Assumes the following prices: $.36/pound nitrogen (N); $.42/pound phosphorus pentoxide (P_2O_5); $.32/pound potassium oxide (K_2O). Historical prices used were 2017 through 2021 and were obtained from Illinois Production Cost Report.

In 2015, 16 percent of dairy production occurred on farms with no crop production, reducing their ability to obtain value from their manure (MacDonald et al., 2018). The midpoint inventory of dairy cow operations was 1,300 cows in 2017 (MacDonald, 2021).

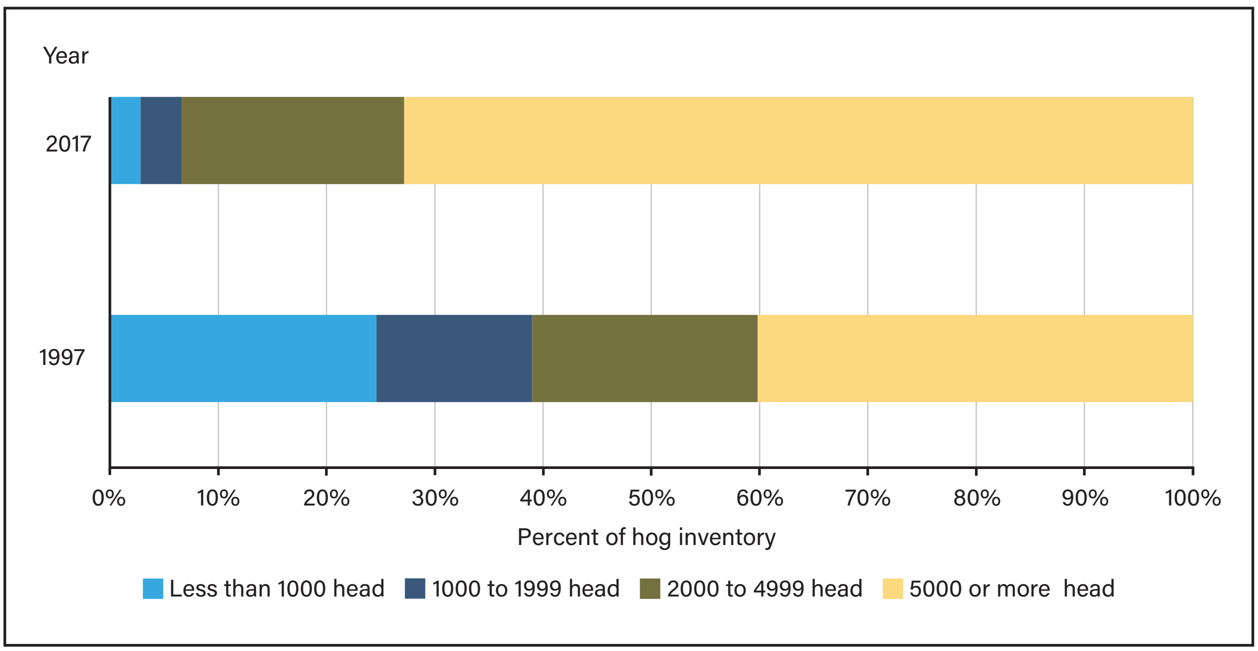
Swine

Historically, most hogs were fed to market weight in Iowa, Illinois, and Minnesota—Corn Belt States where corn for feed was plentiful. Hog production expansion in the late 20th century occurred in economically depressed regions where farmers were looking for alternative uses for their land. North Carolina tobacco farmers curtailing tobacco production could make a living by putting a hog barn on relatively few acres of land. Remote locations such as the Plains States developed hog feeding operations that followed the beef cattle feedlot model (Texas Pork Producers Association, n.d.). That is, farmers imported the grain they needed from other regions. Lagoons became popular in these areas because the need for nitrogen on only a few acres of land lowered the manure's fertilizer value (Jones, 2006). Also, environmental regulations were based on nitrogen applied to land, so nitrogen volatilization reduced the required acres for application.

Hog production growth over the last 20 years has mostly occurred in the corn belt states (USDA Censuses of Agriculture). The emergence of large hog companies (i.e., integrators) seeking growers (i.e., contract growers) fostered moving hog production back to the Midwest. The integrators provide the hogs and feed. The farmers provide housing, labor, and utilities for the hogs. Manure generated by the pigs belongs to the farmers, who must manage the manure and can receive whatever fertilizer value it contributes to their crop enterprises.

Most hogs are raised in confinement—either outdoors or indoors. Few hogs are allowed to roam fields since they might become feral or destroy field vegetation. Most are raised in buildings. Hog farms have become much larger in the past several decades (figure 3). More than 70 percent of hogs in 2017 were raised on farms with 5,000 or more head of inventory.

Figure 3
Number of hogs raised by size of farm in 1997, 2012, and 2017



Note: Figure shows the number of hogs raised by farms in four farm size categories.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, 1997 and 2017 Census of Agriculture.

A typical hog barn houses from 1,200 to 2,480 head. Given most hog farms have at least 5,000 head, farms commonly have 2 or more pig barns. Many early confinement hog facilities used lagoons to store manure, but most newly constructed facilities store manure in a pit as slurry. The slurry retains more excreted nitrogen and captures less rainwater, so the manure has higher nitrogen and dry matter levels.

A 5,000-head grow-finish hog facility, with an under-barn slurry pit, will market about 12,000 hogs/year. These hogs will produce about 2.2 million gallons of slurry manure, containing 54.7 tons of stored nitrogen—of which 43.6 tons are available for plant growth—and 45.9 tons of P_2O_5 (phosphorus) and 32.8 tons of K_2O (potassium) (Lorimor et al., 2000). To meet the nitrogen needs of corn yielding 175 bushels per acre, a hog operation of this size would require 497 acres annually for applying manure. The manure's value as a fertilizer replacement for a corn-soybean rotation would total $72,000 per year in this situation. If applied to meet the phosphorus needs of a corn-soybean rotation, 875 acres would be required annually. In 2015, 31 percent of swine production occurred on farms with no crop production.

Poultry

Poultry production encompasses raising chickens and turkeys for meat and eggs. Broiler chickens for meat account for 67 percent of poultry sector sales, eggs account for 21 percent, and turkeys account for 12 percent (U.S. Department of Agriculture, 2020). The overwhelming majority of broiler farms are located in the southeastern United States. Turkey and egg production are more geographically dispersed within the United States. Small and midsize family farms, with production contracts, contribute 84 percent of poultry value (Whitt et al., 2020).

Farmers need to manage 3.5 pounds of litter for each 5.7-pound broiler chicken raised (Putman et al., 2017). Litter includes the bedding (e.g., rice hulls, wood chips, peanut hulls) and excreta from the chickens. Litter has a high dry matter content compared to other animal species.

A 21,000-square-foot poultry barn houses 27,460 birds at any one time (National Chicken Council, 2020). Each year, a facility of this size produces 135 tons of litter (Sharpley et al., 2009). Analysis of litter samples in Mississippi indicates that each ton of litter contains about 47 pounds of nitrogen, 73 pounds of P_2O_5 (phosphorus), and 60 pounds of K_2O (potassium). Surface application of poultry litter would reduce the amount of plant-available nitrogen to 24 pounds per ton of litter. The annual litter from 1 house applied to meet the phosphorus needs of a corn-soybean rotation would require 68 acres of land. The value of 1 year's litter would be about $6,700.[3] If the manure were applied to meet a corn crop's nitrogen needs, then only 18 acres would be needed, and the manure's value would decrease to $2,700 per year. These values do not account for the cost to apply manure to land. Many poultry farms would have multiple barns and, therefore, could fertilize multiples of land noted here.

In 2015, more than 52 percent of poultry production occurred on farms with no crop production. In 2011, about one-third of poultry litter fertilized fields were managed by the farmer raising the birds. Two-thirds were transported off the operation generating the litter. About half of the litter removed was sold; the other half was exchanged for a service, given away, or hauled off for a fee (U.S. Department of Agriculture, 2018).

Fed Cattle

Cattle are fed in outdoor feedlots for 90 days to 300 days, depending on their weight when entering the feedlot. Most U.S. feedlot operations have less than 1,000-head capacity. Feedlots with more than 1,000-head capacity make up 5 percent of the feedlots but market 80 percent to 85 percent of fed cattle (Knight,

[3] Assumes following prices: $.36/pound N; $.42/pound P_2O_5; $.32/pound K_2O.

2020). Because cattle are fed for less than 1 year, the annual number of animals fed will be greater than the capacity. The 2017 Census of Agriculture reports the midpoint fed cattle feedlot sold 42,300 animals annually (MacDonald, 2020). Most cattle feedlots are located in the U.S. Great Plains, and 68 percent of cattle feedlots do not have cropland.

Most fed cattle feedlots manage solid manure. A feedlot of 42,300 head sold would likely produce 207,270 tons of manure each year. The manure would supply about 611 tons of recoverable nitrogen, 725 tons of recoverable P_2O_5 (phosphorus), and 1140 tons of K_2O (potassium) (Lorimor et al., 2000). Application to meet the nitrogen needs of corn yielding 165 bushels per acre requires 8,128 acres annually. Manure's value as a fertilizer replacement for a corn-soybean rotation would total $1,100,400 per year.[4]

Manure Storage

The manure storage system a farm chooses will affect the manure's composition (e.g., moisture content), fertilizer value, and potential uses (e.g., energy production, industrial products). The system will also dictate the equipment a farm needs to manage the manure. Farms with beef cattle, and poultry are most likely to use dry storage. Farms with pigs and dairy cows can store manure as liquids in lagoons, slurries in pits, or dry manure.

Occasionally, existing production facilities can be retrofitted or modified to accommodate value-added opportunities for manure. However, farms commonly make decisions about the storage systems they will use before constructing new animal production facilities. Consequently, the effectiveness of State and Federal programs designed to increase rural economic opportunities from animal production are more likely to succeed if they consider the entire production system—including manure storage and management.

In some cases, farms may adopt systems that reduce manure's water content. Removing liquid preserves the manure's nitrogen content and increases its value. If nearby crop demand for nitrogen and phosphorus is low, preserving nitrogen doesn't necessarily increase the manure's value. It can instead necessitate transport and access to more acres on which to apply the manure under existing Federal regulations. Keeping water out of manure—or storing the manure in a dry form—decreases manure transport costs.

Farms can introduce water reduction technologies at the production stage or the manure storage stage. Wet-dry feeders in swine production have been shown to reduce water in pig slurry manure and make the slurry a more concentrated source of fertilizer nutrients. Lagoon or pit covers can both conserve nitrogen and prevent rainwater from diluting the manure, as well as reducing odor issues. Solid-liquid separation can separate manure's nutrient-dense fraction from the water so that both fractions can be managed for maximum benefit, as discussed in the second half of the report.

Manure Use as Fertilizer

Manure supplies nitrogen, phosphorus, and potassium to growing crops. Manure's nitrogen-to-phosphorus ratio is usually lower than the ratio required by the crop being fertilized. Therefore, manure can complement but not perfectly substitute for commercial fertilizers. The nitrogen-to-phosphorus uptake ratio of crops may require that manured fields also receive commercial fertilizers to fully meet crop nutrient needs. Applying manure to meet the phosphorus needs of a crop may not supply enough nitrogen. This mismatch of nutrient demand and supply increases the cost of crop fertilization—and may reduce manure's perceived value—because when applying both manure and commercial fertilizer to a field, two trips through the field increase the application costs. Alternatively, if manure is applied to meet a crop's nitrogen needs, then it will oversupply phosphorous, which will build up in the soil. Overapplication can also have negative environmental impacts (Paudel et al., 2009).

[4] Assumes following prices: $.36/pound N; $.42/pound P_2O_5; $.32/pound K_2O.

For applied manures, the nitrogen-phosphorus ratio ranges from 0.2 to 3.0.[5] Manure stored in lagoons tends to have lower nitrogen-to-phosphorus ratios than manure stored as a solid or slurry. Lagoon storage loses nitrogen into the atmosphere and stores phosphorus in the sediment, on the bottom of the lagoon, where it may remain for years. Poultry manure's nitrogen-to-phosphorus ratio also tends to be lower than the ratios for cattle and hog manure.

Manure nutrient levels vary within and across farms, so manure must be tested to be used efficiently. Manure tests measure the nitrogen and phosphorus in manure samples and have typically required sending samples to a laboratory. Sampling is subject to variation due to manure mixing, the sample's timing relative to timing of manure's use as a fertilizer, and other considerations. On-farm, real time testing methods are being developed. A survey of Midwest animal farmers from Ali et al. (2012) found that testing manure's nutrient content was more likely to be done if the manure was transferred to another farm, a farm paid for the manure, a formal contract existed, and the manure was transferred a farther distance.

Unlike commercial fertilizer, manure does not come with a guaranteed nutrient analysis. To reduce the risk of insufficient crop nutrients, farmers may apply more manure-supplied nitrogen than the crop requires or may supplement manure applications with commercial fertilizer.

USDA ARMS data indicate that only 44 percent of farmers who applied manure to corn also reduced commercial fertilizer applications to corn because of manure applications. Those who reduced commercial nitrogen use indicated they reduced it by 46 percent. Both statistics indicate that there is room for improved nutrient management to capture its nutrient value more fully.

Manure Use by Crop

Almost 19 million acres, planted to 7 major U.S. field crops, received manure in 2020—7.9 percent of the 237.7 million acres planted to these crops. In 2020, more acres were planted to corn (90.8 million acres) than any other crop, and a larger percentage of corn acres received manure than any other crop (16.3 percent). Corn was planted on 79 percent of the cropland that received manure (table 2). Hay acreage and grassland also receive manure. USDA data from 2006 shows that 26 percent of manured acres were hay and grass acres (MacDonald et al., 2009).

[5] Table 10 in the appendix lists nitrogen-to-phosphorus ratios for different sources of manure applied to land in different ways.

Table 2
Manure applications to major field crops, 2020

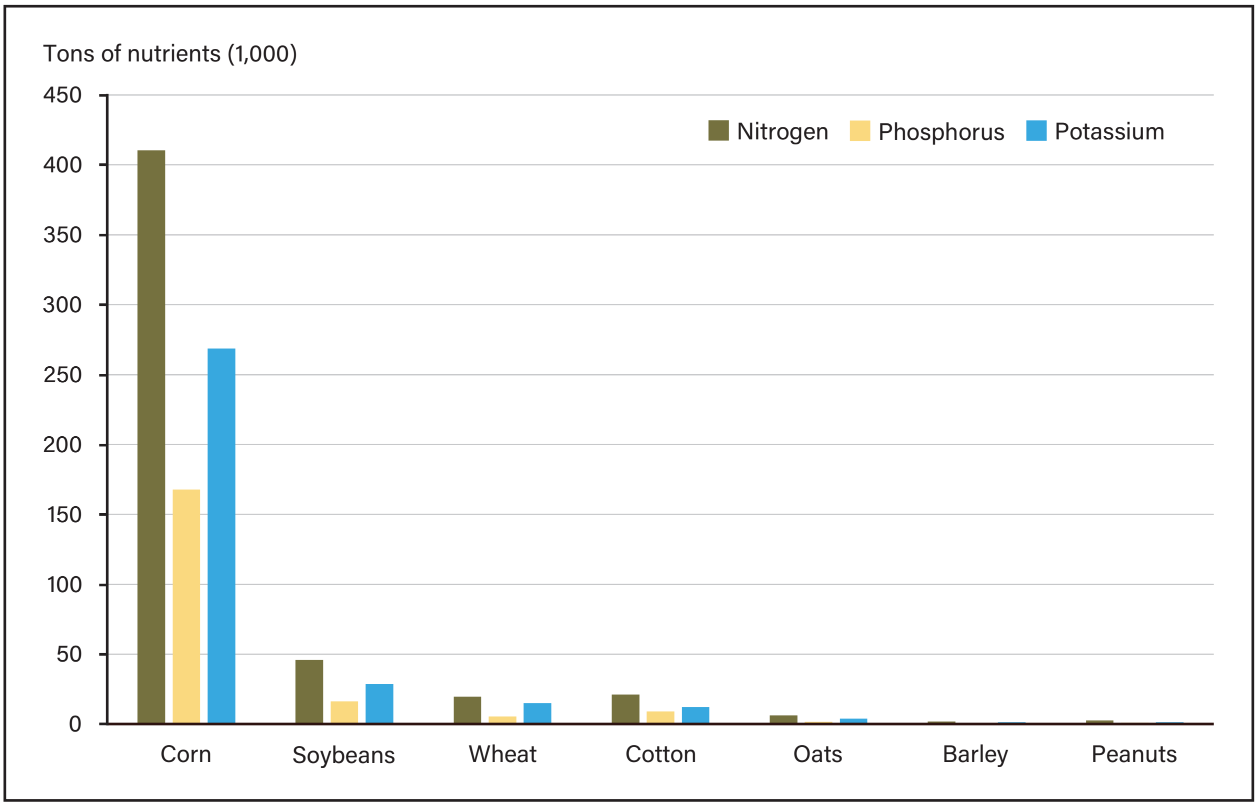
Commodity receiving manure	PII Year*	Share of crop acres manured (percent)	2020 acres (000)		Share of all manured acres (percent)
			Planted	Manured	
Corn	2016	16.3	90,819	14,822	78.8
Soybeans	2018	2.3	83,084	1,884	10.0
Wheat	2017	2.0	44,349	908	4.8
Cotton	2019	4.2	12,093	505	2.7
Barley	2019	5.0	2,726	137	0.7
Oats	2015	12.0	2,984	358	1.9
Peanuts	2013	12.2	1,664	203	1.1
Total		7.9	237,719	18,818	100

*PII Year = Year in which Agricultural Resource Management Survey (ARMS) Phase II Survey was conducted for a specific crop.

Source: USDA, Economic Research Service. 2020 planted acreage estimates are from USDA, National Agricultural Statistics Service (NASS) Acreage report. Manure share is based on USDA, ARMS Phase II surveys, 2013 through 2019. 2020 manure acreages are estimated by multiplying 2020 planted acres by the share of crop acres manured from the 2013-19 ARMS Phase II surveys

Corn acres received more than 410,000 tons of manure nitrogen, 81 percent of total applied nitrogen (figure 4). The nutrient tonnage reported in figure 4 is less than the quantity of nutrients excreted Nitrogen can volatilize before being land-applied, and phosphorus can settle to the bottom of lagoons where it may remain for years.

Figure 4
Total tons of land-applied manure nutrients, by crop



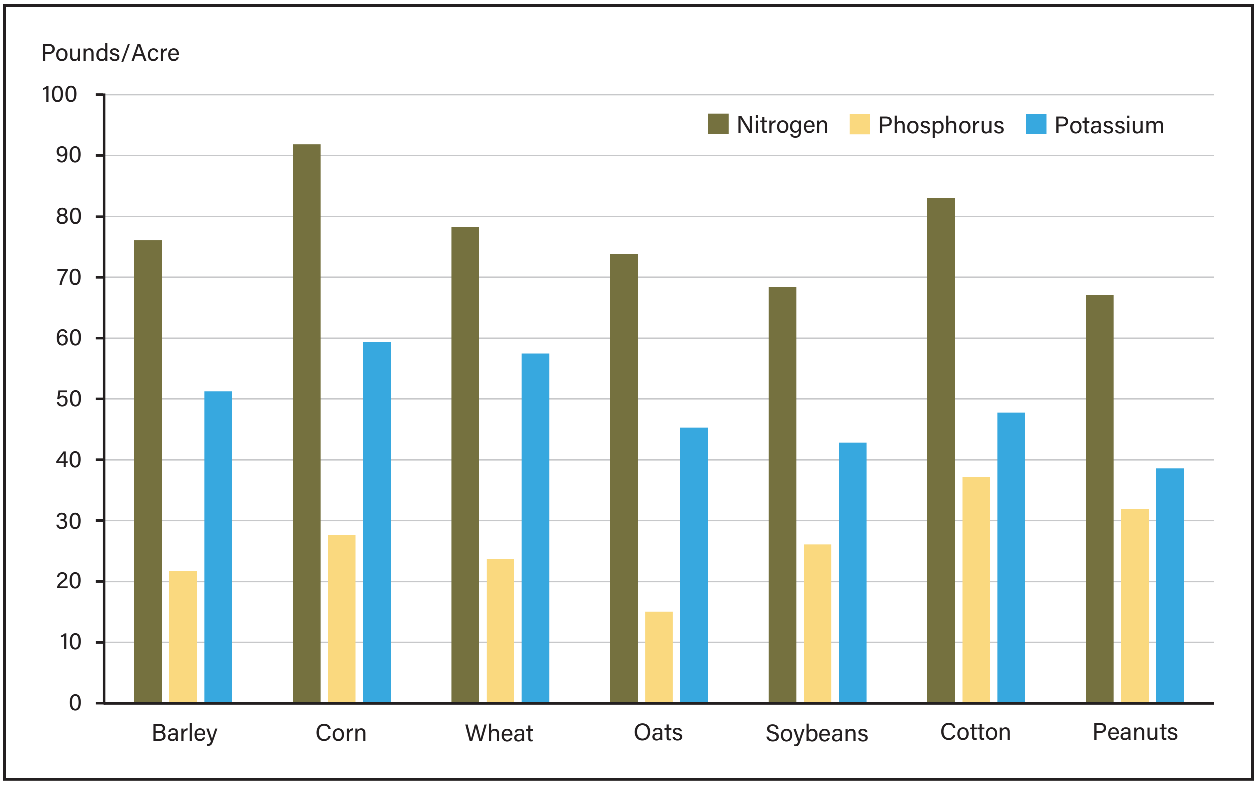
Note: Manure nutrients are calculated based on the reported manure quantity applied, animal species—and the whether the manure is lagoon liquid, slurry liquid, and dry or semi-dry (MWPS-18, 1993; Lorimor et al. 2004).

Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–19.

Corn also receives the highest manure application rates—92 pounds of nitrogen per acre—followed by cotton, wheat, barley, oats, soybeans, and peanuts (figure 5). Crop rankings for phosphorus and potassium application rates differ slightly from nitrogen—with the amounts in decensding order for phosphorus as cotton, peanuts, corn, soybeans, wheat, barley, and oats and for potassium as corn, wheat, barley, cotton, oats, soybeans, and peanuts (figure 5). As legumes, soybeans and peanuts do not typically benefit from nitrogen fertilization and have the lowest manure nitrogen application rates. Manure applied to soybeans and peanuts is valued primarily for its phosphorus and potassium.

Figure 5

Manure nutrient application rate, by crop



Note: Figure shows the manure nutrient application rate by crop.

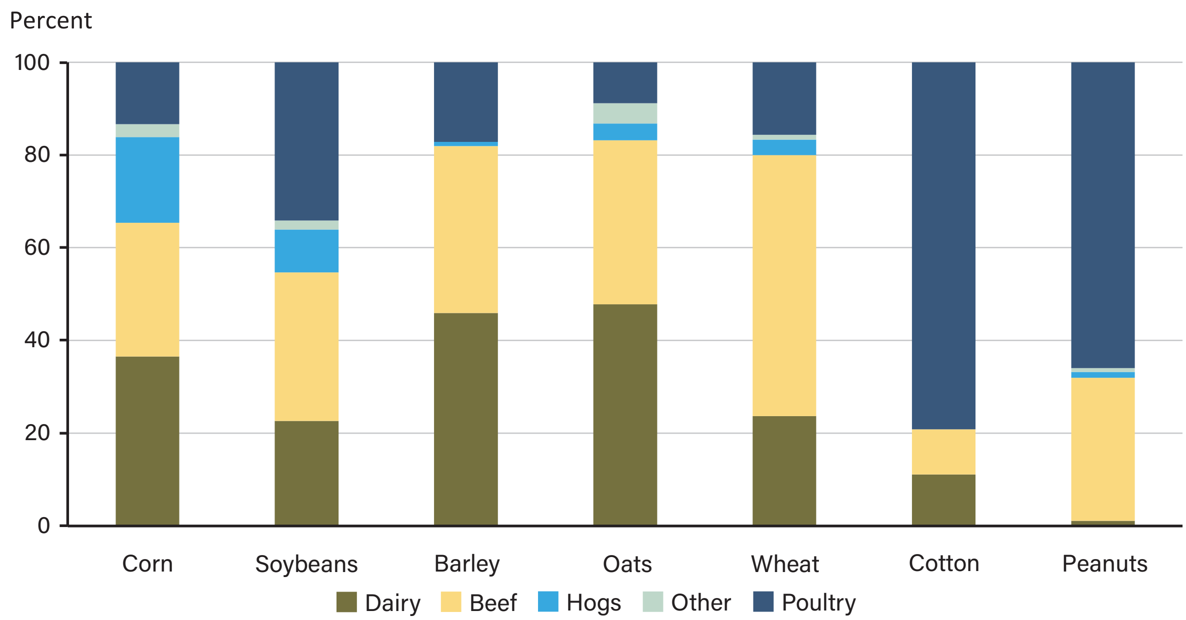
Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–19.

The extent to which crop farms use manure and the type of manure they use depends on farm location, farm size, farming system, production practices, and other farm characteristics.

Animal production and manure management differ by region. Because most hogs are produced in the Midwest, hog manure is applied predominately to corn and soybeans. Most chickens are raised in the southeastern United States—so, as a result—most manure applied to cotton and peanuts is sourced from poultry farms (figure 6).

More than 50 percent of manured wheat and acres receive beef manure. Beef is produced mainly in the Great Plains, where most wheat acres are planted. Dairy, produced in the western, midwestern, and northeastern United States—supplies the largest share of manure applied to corn, barley, and oats.

Figure 6
Percent of manure applied from each source, by crop



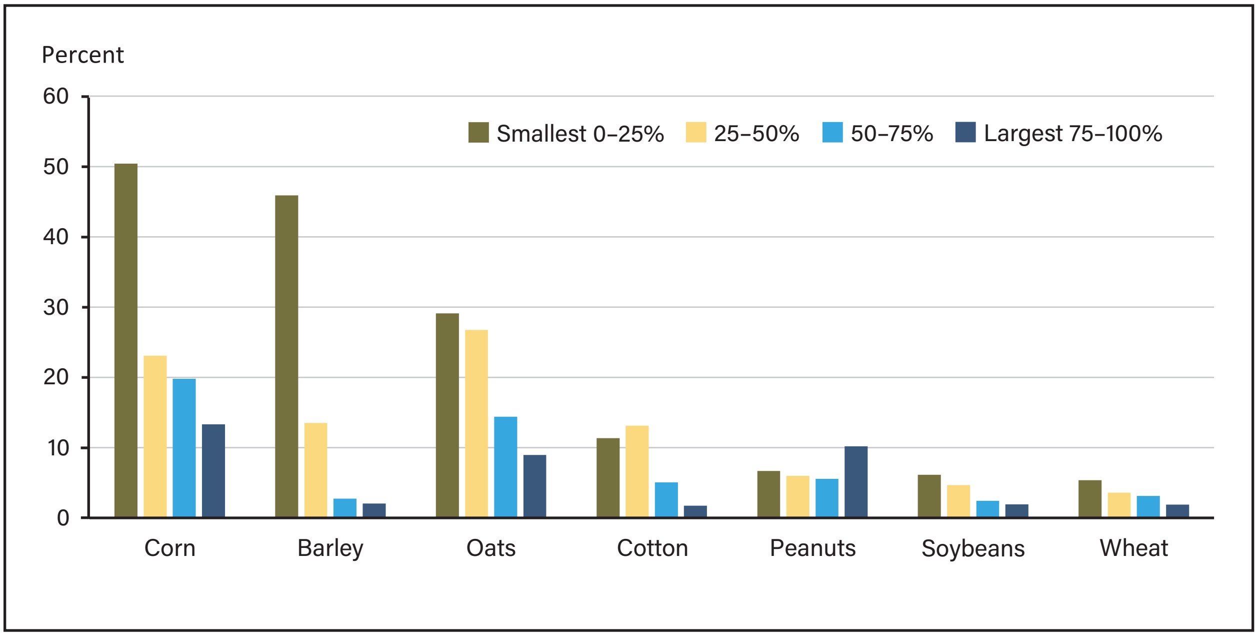
Note: For each crop, the figure shows the share of manured acres coming from each animal manure source.

Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–19.

For most crops, small-scale farmers are more likely than large-scale farmers to apply manure to their crops. Producers of the major field crops were sorted into four size classes, based on their planted acres for that crop (figure 7). Half of the smallest quartile of corn farmers applied manure, and only 14 percent of the largest quartile of corn farmers applied manure to corn.

This pattern may be partly explained by specialization: Larger crop farms are more likely to specialize in crop production and not raise animals. Operators of large farms may place a higher value on their own time and face labor constraints, and thus prefer commercial fertilizers, which can be applied more precisely and quickly than manure.

Figure 7
Farmers who applied manure, by crop and size

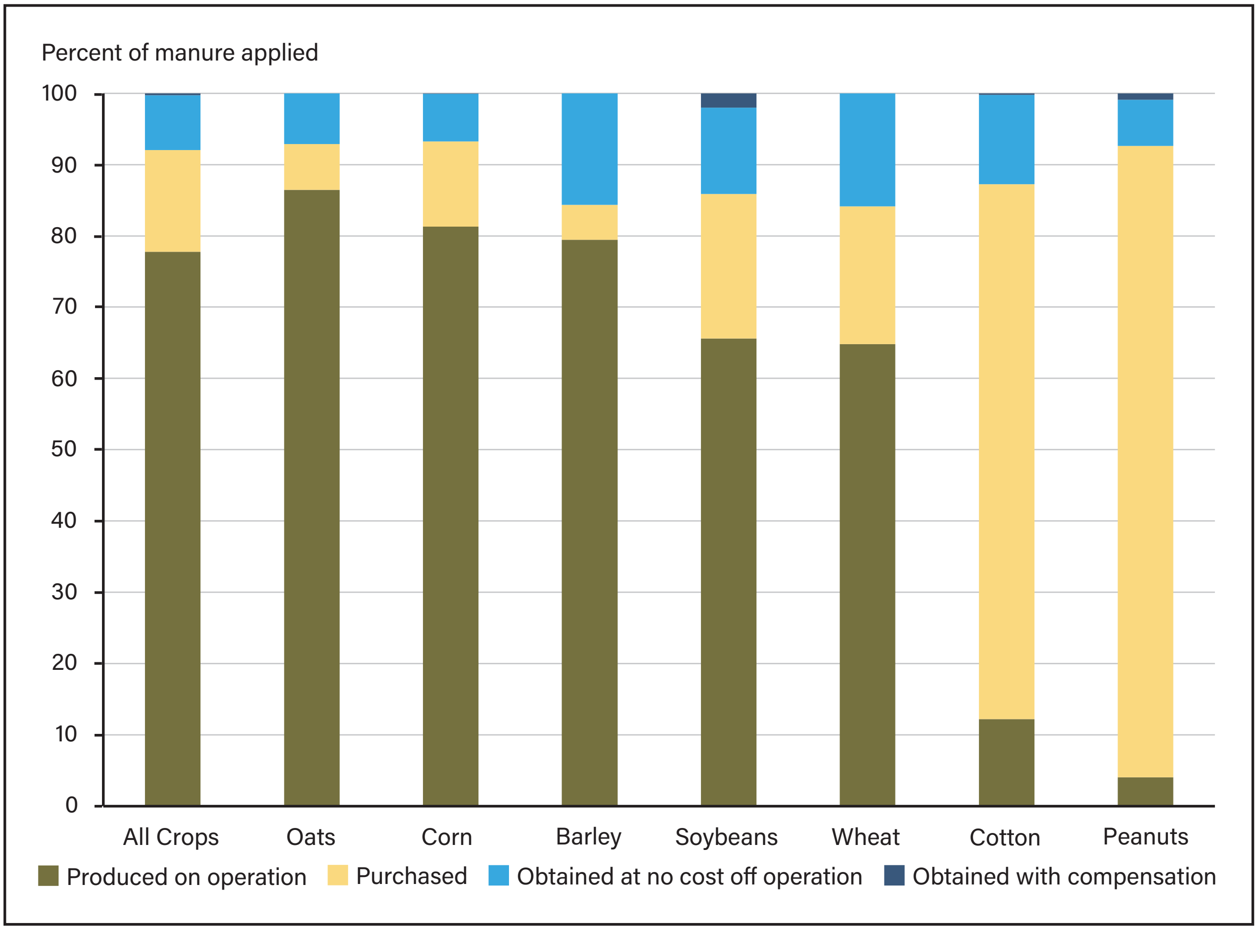


Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–19.

Manure Acquisition

In terms of manure use, animal producers most commonly apply manure to their own cropland (figure 8). For all crops, 78 percent of manure is applied to land controlled by the animal producer, 14 percent is purchased by crop farmers from animal farmers, and 8 percent is given for free to other farmers. Less than 1 percent of manure produced is disposed at a cost to the animal producer. Only on cotton and peanut acres are the majority of manure applied not from the animal farm producing the manure.

Figure 8
Source of manure applied, by crop



Note: The figure shows the percent of each source of the manure applied to crops.

Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–19.

Merging information from figure 6 and figure 8 also suggests regional and species differences in manure acquisition. Poultry litter is the manure most likely to be purchased and applied to cotton and peanuts grown in the southeastern United States. Most manure applied to corn acreage is produced or managed by the animal producer—most likely Midwest dairy and swine farms or western U.S. beef feedlots.

Few animal feeding operations give away manure at no cost—or receive minimal compensation—because of the manure nutrients' fertilizer value. Comparing Agricultural Resource Management Survey (ARMS) data from 2015 to 2019 and 2003 to 2006 shows that instances of obtaining manure at no cost decreased between those two periods. Manure that is transferred without cost likely originates from a concentrated animal feeding operation that lacks sufficient land to use the manure. This situation may indicate excess manure supply in the local area, so the operation has few options other than giving away the manure.

On the other hand, crop farmers purchasing manure indicate that they value manure, and the animal producers know manure is a valuable product. Table 3 indicates what type of manure was purchased by crop farmers and in what region of the country. As indicated earlier, this scale is not relevant for particular farms due to transportation costs, but it shows that poultry manure, the most nutrient-dense manure, is the most common manure to be purchased in almost all regions. Hog manure is only purchased in three regions.

Table 3
Crop farmers reporting having purchased manure by farm production regions

Region	Beef	Dairy	Hogs	Poultry
Appalachia				17,388
Corn Belt	1675	3,453	9,175	20,398
Delta				3,361
Lake States		3,037		4,121
Mountain	691	1,064		105
Northeast	32	558		11,183
Northern Plains	5,438			4,087
Southern Plains	1,570	15	14	1,429
Southeast			26	10,278
Pacific	105	231		321

Note: For a map of USDA farm production regions, see Appendix D.

Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–2019. Surveyed crop farmer data are weighted to represent the full population of crop farms by region.

Transferring manure to crop farms without animals generates some controversy as it may allow manure application to occur without a nutrient management plan, a regulatory document specifying what amounts of nutrients will be applied on what fields at what time, which is intended to limit excess nutrient applications. Fourteen states require farmers receiving manure to apply the manure in the same way animal feeding operations would apply it (see table 5 last line). For more information about nutrient management plans, see this report's "regulatory and policy environment" section.

Marketing Manure as a Fertilizer

Farms or other agribusinesses may find opportunities in marketing manure as a fertilizer. The poultry industry has most successfully marketed manure and transported it longer distances.

To market manure as a fertilizer, farms, and agribusinesses may choose from multiple business models. One business model involves a litter hauler taking possession of the litter, hauling it to locations where it is valued as a crop fertilizer, and applying it to land. Because of litter's nitrogen-to-phosphorus ratio, some litter haulers have "bundled" the litter with commercial fertilizers. In other words, they will only provide litter to farmers who also agree to purchase commercial fertilizer. In effect, the litter supplier coordinates a balanced fertilizer program for the crop receiving the manure. This model allows all the litter nutrients to be valued and provides additional income in the form of commercial fertilizer sales and application.

The nutrient consistency and guaranteed analysis of commercially sold fertilizers is highly valued by crop producers. Manure samples can be sent to labs for nutrient analysis, but the manure may need to be land-applied before the lab results are received. Rapid manure testing has been suggested as a means to increase the value of manure.

Marketing manure includes assuring the crop producer that manure can be land-applied quickly without negatively impacting the field and in a way that makes the nutrients plant-available. Many contract applicators are using equipment that meets these objectives, but legacy equipment[6] is still being used that reduces manure's value.

[6] Legacy equipment is old technology equipment still in use but not considered a best practice.

Manure Use in Organic Food Production

Manure from conventional animal operations can be used in organic food production under National Organic Program standards (Code of Federal Regulations as cited in Wander, 2019). To ensure food safety and protect water quality, food producers must take precautions when using manure as a fertilizer. For example, raw manure cannot be applied within 120 days of harvesting a food crop that may be contaminated by soil that received raw manure. Specific regulations dictate how to treat manure—treatment processes include composting or heat treatments—if it will be used closer to harvest. Weed seeds and plant and animal disease organisms are concerns to address through appropriate manure treatment processes, for example composting that reaches high temperatures for specific lengths of time. Additionally, the organic standards require manure to be stored appropriately and applied at agronomic rates. It also should be incorporated prior to planting. While raw and composted manures are approved organic fertilizers, ash from manure used to generate energy is not approved.

Both the European Union and Canada require manure nutrient testing as part of organic production (Wander, 2019). Testing is highly recommended because nutrient and water content can vary widely based on the species that produced the manure, the production system, and handling practices. Manure testing is more expensive than soil testing, with costs ranging from $30 to $60 per sample (Wander, 2019), although some States, such as North Carolina, subsidize it (Hicks, 2020). Manure's nitrogen-phosphorus imbalance potentially can be addressed in organic production systems by using cover crops and green manures (Carr et al., 2020).

Manure Application

Farms select an appropriate manure application method, based on the type of manure being applied, the crop receiving the manure, and other farm-specific needs and constraints. Broadly speaking, farms may choose from five manure application methods: 1) surface application without incorporation, 2) surface application followed by incorporation within a short time, 3) subsurface application, 4) sprayed on via an irrigation system, and 5) side-dressing. When feasible, subsurface application or incorporation of manure (following surface application) conserves more nutrients and increases the value of manure more than surface application without incorporation than application via an irrigation system.

Surface Application Without Incorporation

Surface-applying manure without incorporation is the simplest manure application method. It requires the least specialized equipment and the least powerful tractors. Surface applications can be made relatively quickly because the equipment can easily and quickly move over the field, resulting in lower labor and fuel costs. Surface application normally has a larger application width as the manure is flailed or sprayed out of wagons (Smith et al., 2014).

Despite the ease at which manure can be surface applied without incorporation, this management practice leaves manure most susceptible to losses of nitrogen through ammonia volatilization (Smith et al., 2014). The conversion of liquid ammonium (NH_{4+}) to gaseous ammonia (NH_3) is greatest at the soil surface where manure is exposed to air, wind, warming from the sun, and has little soil contact. When manure is below the surface and in contact with soil, conversion from ammonium to ammonia is reduced (Smith et al., 2014). Furthermore, manure at the soil surface is susceptible to washing off the field with rainwater, which transports both nitrogen and phosphorus to waterways.

Surface Application with Incorporation

Incorporating surface-applied manure into the soil is generally recognized as a better management practice than leaving the manure on the soil surface. Manure is spread on the soil surface and then mixed into the soil with a tillage implement. By incorporating manure into the first few inches of the soil, manure has greater contact with soil particles, ammonium binds to soil, and conversion to gaseous ammonia is reduced. Surface application followed immediately with incorporation reduces ammonia emissions by at least 90 percent. Waiting to incorporate manure (following surface application by just 4–6 hours) can result in 60 percent greater ammonia losses through volatilization, compared to immediate incorporation (Webb et al., 2010) Reducing ammonia losses increases the value of the manure and reduces odor concerns, compared to surface application without incorporation. In areas of highly erosive soils, the soil disturbance caused by incorporation of manure can contribute to greater transport of nitrogen and phosphorus nutrients into streams through erosion, especially if rain occurs shortly after application. Furthermore, incorporation is limited to fields where tillage is possible, which excludes, for example, areas of perennial grasses and no-till crop production. In these areas, subsurface application is a more compatible management option (Webb et al., 2010).

Subsurface Manure Applications

To accomplish subsurface manure application, equipment incorporates or injects manure below the soil surface at the time of application. Typically, this application method involves creating slits in the soil and placing the manure in those slits (Webb et al., 2010). Examples of commercially available equipment in the United States that apply liquid manure below the soil surface include chisel, disk, and knifing implements. Equipment to apply dry manure, including poultry litter, below the soil surface is being developed (Dell et al., 2011).

Subsurface application methods allow farms to precisely apply manure to specific locations. Also, because subsurface methods do not turn over the soil, they reduce the possibility of manure leaving the field, and they preserve the value of manure-supplied nutrients. Placing liquid swine or cow manure below the soil surface reduces ammonia nitrogen volatilization and losses. The reduction in volatilization depends on various factors including injector design, injection depth, and soil moisture. Reducing ammonia nitrogen losses by 40 percent to nearly 100 percent, compared with surface application without incorporation, is typical in crop and forage systems (Dell et al., 2011). Preventing ammonia nitrogen loss preserves the manure's fertilizer value, and it can result in better nitrogen recovery of crops (Webb et al., 2010).

Two concerns with subsurface applications are: 1) nitrogen leaching into groundwater and 2) increased nitrous oxide emissions. Evidence suggests that subsurface manure application can increase the risk of nitrogen leaching to groundwater. This is mostly a concern in areas with shallow tile drainage or a shallow water table or when manure is applied in excess of crop needs (Dell et al., 2011). Injected manure might also increase nitrous oxide, a potent GHG, emissions during the denitrification process (Adair et al., 2019). However, some researchers conclude the likely NH_3 (ammonia) savings outweigh the possible risk of nitrous oxide loss (Webb et al., 2010).

With respect to subsurface application's effect on phosphorus, Rotz et al. (2011) found subsurface manure application reduced soluble phosphorus losses by approximately 70 percent to 75 percent on different sized farms with various feed management practices and animal types. Other studies have found phosphorus runoff reductions to range from 70 percent to 95 percent (Maguire et al., 2011).

Subsurface manure application may also provide air and water quality benefits (Dell et al., 2011). Some evidence suggests subsurface application reduces odors compared to surface application—possibly reducing legal costs associated with animal production.

The impact of subsurface application on crop yield is mixed. Milliron et al. (2019) found injected manure increased rye silage biomass by 42 percent, compared to broadcast application. Other research has shown that injection equipment can damage crops and offset yield benefits linked to subsurface applications (Rodhe and Halling, 2015). Additionally, subsurface injection is not feasible in soils that have a heavy texture, a lot of rocks, or too much slope. In these environments, damage to injection equipment can occur (Dell et al., 2011).

Relative to other manure application practices, injection preserves the most manure nutrients but often costs more because it requires powerful equipment and takes more time. Economic analysis has found subsurface injection to be profitable under some circumstances. Rotz et al. (2011) estimated injection costs and benefits for several types of animal and cropping systems in Pennsylvania. They found mixed results. Shallow disk injection of manure on a swine and beef farm with grass production increased the manure's value more than it increased injection costs. In the same study involving a large dairy farm with corn and grass grazing, manure injection increased costs relative to surface applications but had no impact on revenue.

To address startup costs related to manure injection, custom applicator businesses operate in some regions. These businesses offer manure and fertilizer application services to farms. A 2016 report estimates the cost of injection to be about $10 per acre more than costs for surface application when the activity is performed by a custom manure application business (Milliron et al., 2019).

Custom operators can often spread injection equipment costs over many acres and, therefore, can inject manure for less than it would cost individual farmers to do this activity. However, farmers sometimes prefer incurring the additional expense and doing the work themselves, so they can control the timing of injection and other fieldwork that needs to be done.

Regarding adoption, Gedikoglu et al. (2011) found that Midwest animal farmers were more likely to inject manure if they were from Iowa instead of Missouri, higher farm sales[7], or viewed the practice as profitable. They were less likely to choose injection if they viewed the practice as complicated. This is another reason that custom application may be appropriate for some farmers.

Spraying Through Irrigation Systems

Spraying lagoon liquid through irrigation systems efficiently spreads manure on a crop. It can be done before, during, or after the growing season and onto fields that cannot be tilled (e.g., pasture and hay acreage). Compared with other application methods, spraying liquid lagoon manure volatilizes and conserves the least amount of nitrogen, and such manure has the least value of manure applied through all methods.

Side-Dressing

Side-dressing methods apply slurry manure alongside emerged crops such as corn. This form of precision application gives farmers close control over where they target the manure application, and it supplies manure to crops when they most need the nutrients.

With side-dressing, farms can also time the manure application during a less busy period—after spring field-work is complete and the crop has emerged. During the spring, farms have limited field workdays because of crop planting and waiting for wet field conditions to improve. Many farmers prioritize planting, and some may miss the opportunity to apply in the spring due to inclement weather. Applying manure early in the season (i.e., early spring or the previous fall after harvest) increases the risk of losing manure nutrients through ammonia volatilization, runoff, and underground seepage. Proper timing of side-dressing(s) can minimize some of this nutrient loss.

[7] Farm sales in 2006 greater than $500,000, versus the base of $100,000 to $249,000.

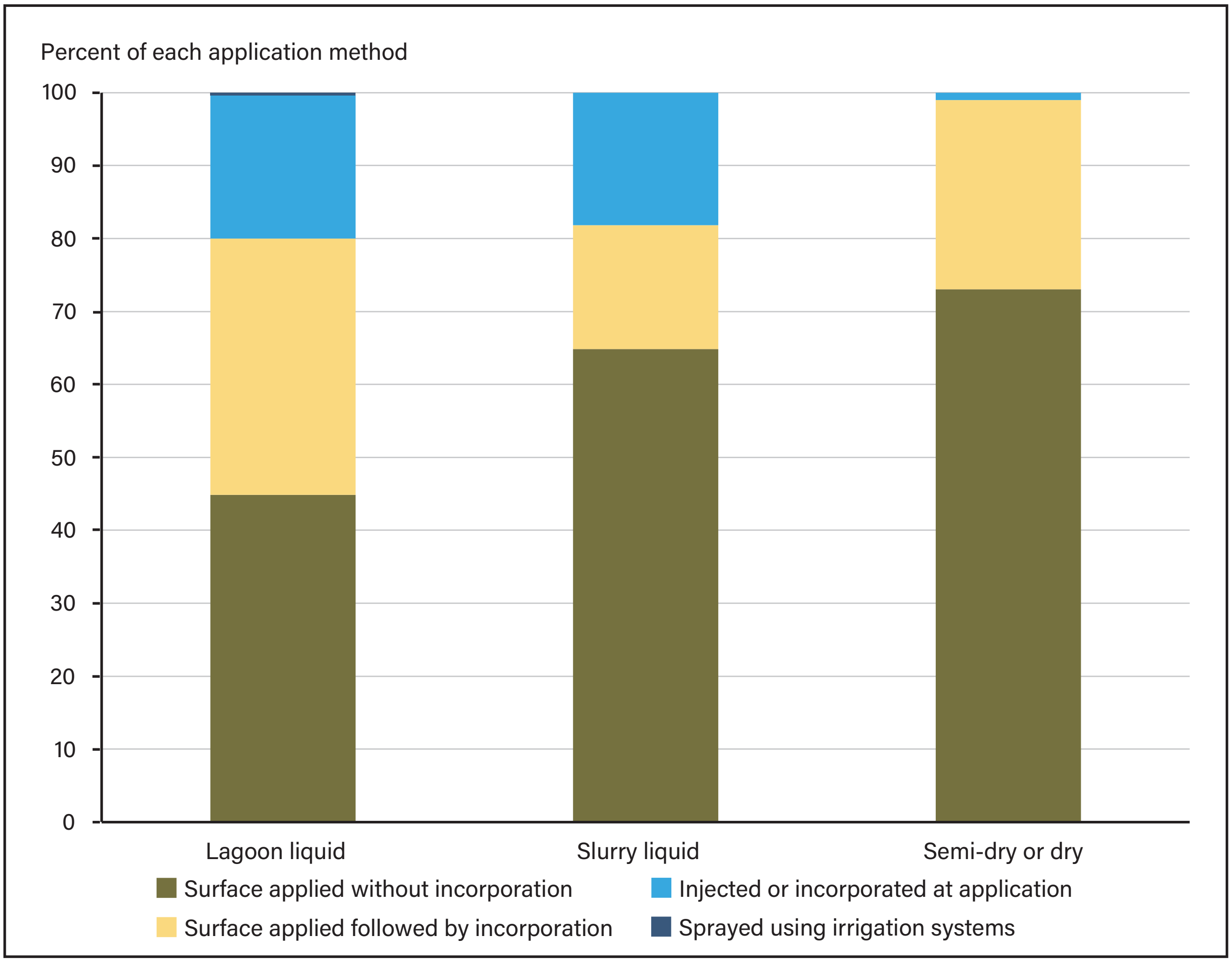
To minimize soil compaction, limit damage to emerged plants and apply large amounts of slurry manure effectively, using a drag hose instead of a manure tanker is a common practice. An on-farm research trial conducted in Ohio applied liquid manure using drag hoses as a side-dress nitrogen source to emerged corn. The plot yield results indicated side-dressing liquid swine manure produced higher yields than applying 28 percent urea ammonium nitrate fertilizer (Arnold, 2020).

Application Methods

The method of applying manure varies depending on liquid content of the manure, which in turn depends on the animal that produced the manure and the manure storage system used. For all types of manure, surface application with or without incorporation is the most frequently used method of application (figure 9). Almost all semisolid or dry manure applications are surface applications. Poultry and beef feedlot manures are typically dry or semisolid. Less than 30 percent of surface-applied manure is incorporated into the soil.

Most lagoon liquid and slurry liquid manures are surface applied. A greater percent of surface-applied lagoon liquid applications involve incorporation compared to slurry liquid. Approximately 20 percent of lagoon and slurry liquid manure is injected or incorporated at application (figure 9). Liquid and slurry manure is typically from swine or dairy farms. Only a small percentage of liquid manure stored in lagoons is sprayed through irrigation systems.

Figure 9
Application methods on corn acres by type of manure

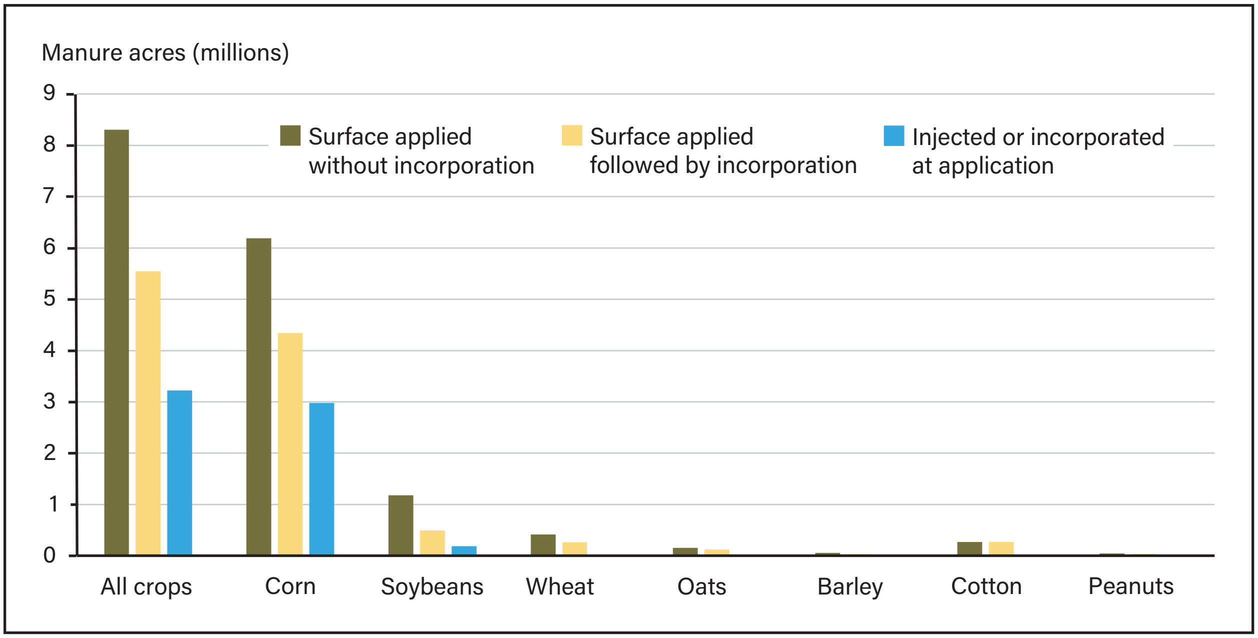


Note: For each type of manure, the figure shows the percent applied by method of application.

Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–19.

The manure application method varies somewhat by the type of crop grown. All the 7 major field crops (except cotton) have a greater percentage of their manured acres surface-applied with incorporation (figure 10). Injected manure acres are less than surface-applied acres with and without incorporation—indicating that significant nitrogen value might be lost. Because of the small number of observations, no data for manure sprayed using irrigation systems by crop are reported.

Figure 10
Manure application method by crop



Note: The figure shows the number of acres to which manure was applied using different application methods.

Source: USDA, Economic Research Service using data from USDA, Agricultural Resource Management Survey (ARMS) Phase II, 2013–19.

Manuresheds and Nutrient Supply and Demand

A "manureshed" refers to the land area surrounding one or more animal feeding operations where manure can appropriately be distributed to meet the land base's crop fertilizer needs and minimize the risk of pollution (Spiegal et al., 2020). If manure availability exceeds the fertilizer needs of an area's cropland, then manure value decreases, or the cost of using manure as a fertilizer increases. Manure generated in locations determined by manureshed methodology to be phosphorus or nitrogen sources—areas with more manure-derived phosphorus or nitrogen than they can use—will have lower manure net value.

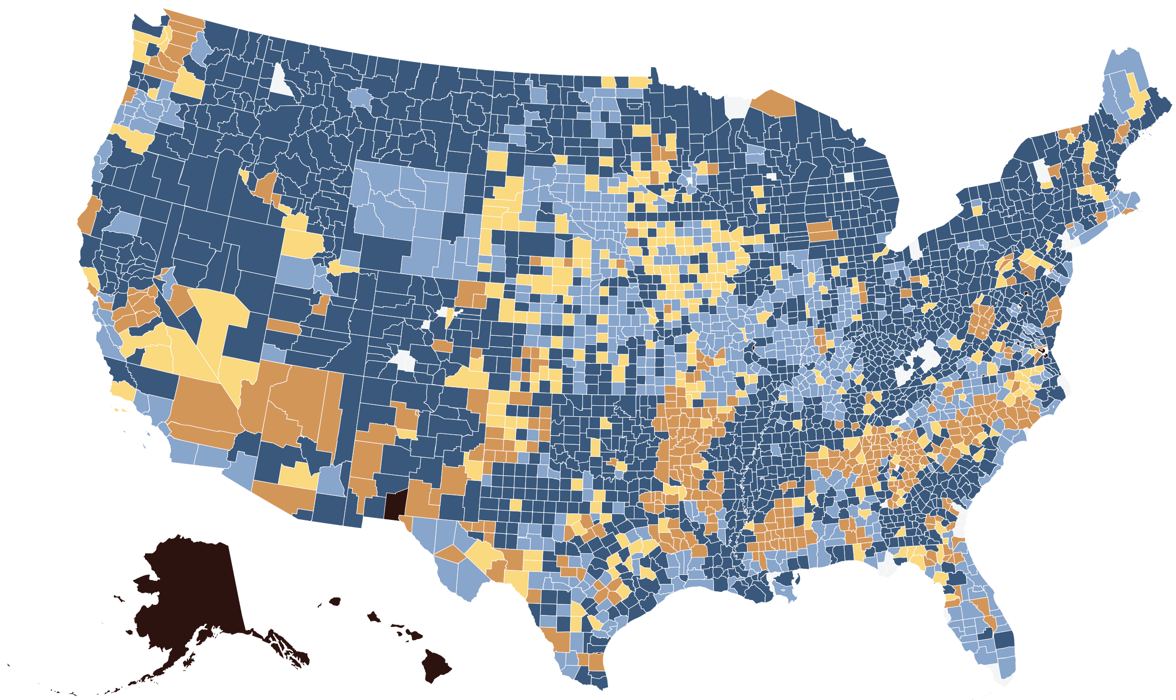
Manuresheds can range in size from the land surrounding a single animal feeding operation to the land in a single county or multiple counties (Spiegal et al., 2020; Saha et al., 2018). In Missouri and Iowa, Ali et al. (2012a) found the average maximum distance that manure from finishing hogs was transported to other farms averaged 4.25 miles, but it was 14.78 miles for broiler manure. Because most manure can be economically transported only short distances, a county-level analysis provides a generalized picture of nutrient sources and sinks within the United States. It does not necessarily provide sufficient detail to address local problems, which will require local information.

Spiegal et al. (2020) integrated 2012 U.S. Census of Agriculture data with other information on crop nutrient needs, manure nutrient content, and nutrient losses in storage and application. Their county-level analysis identified counties as phosphorus or nitrogen sources or sinks. Of the 3,109 counties in the contiguous United States, an estimated 390 counties generate more phosphorus than crop production in those counties can use, according to Spiegal et al. (2020). These are called "phosphorus source" counties. One hundred counties generate more nitrogen than can be used, and they are called "nitrogen source" counties (figure 11). All but one of the counties identified as a nitrogen source was also a phosphorus source. These estimates are in line with those of Gollehon et al. (2016) who estimated that 205 of 3,070 U.S. counties in the 2012 Census of Agriculture database produced excess manure (i.e., more manure nutrients than could be effectively used by crops grown in those counties).

Figure 11

Counties classified with respect to manure nutrient source and sink potential for a) phosphorus and b) nitrogen in 2012

Phosphorous sinks and sources



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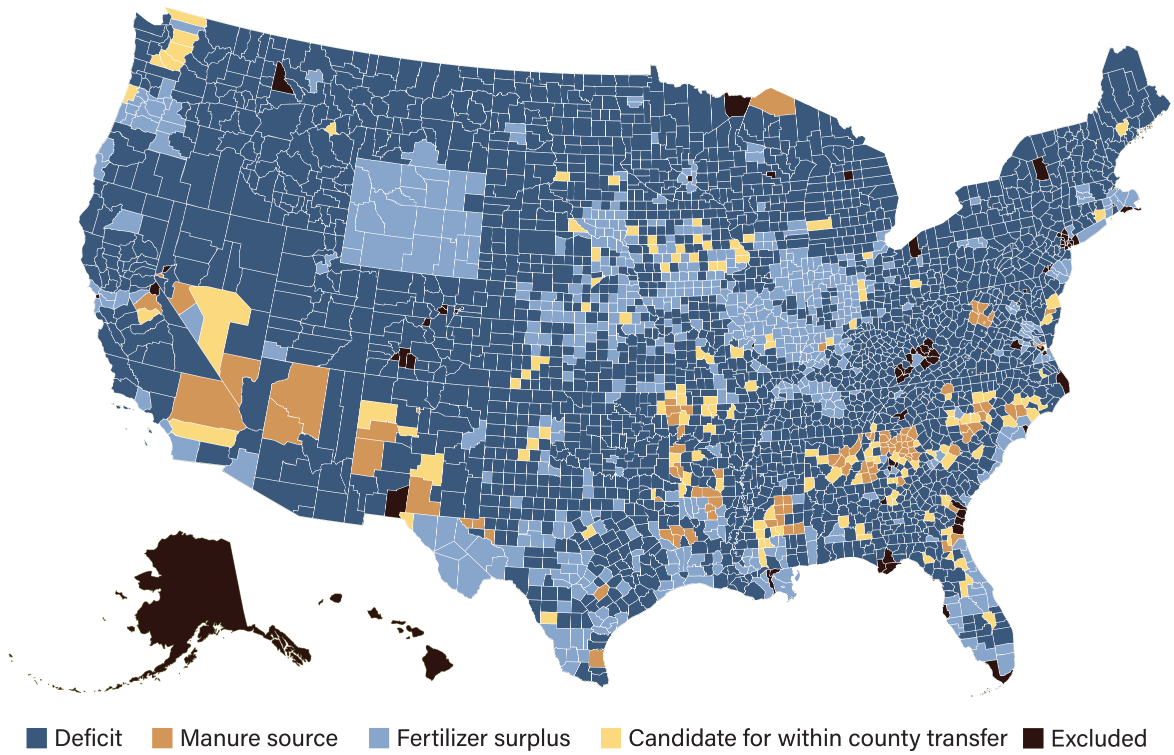
Nitrogen sinks and sources



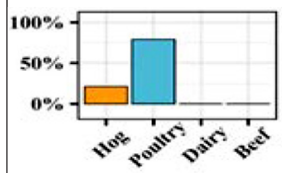
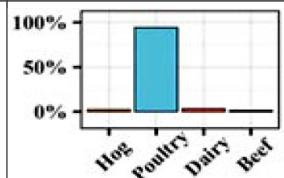
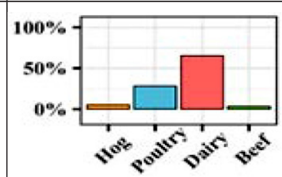
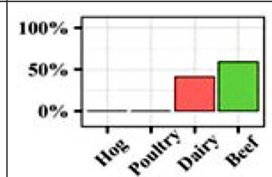
Note: Data exist only for the contiguous 48 States.

Source: USDA, Economic Research Service using data from Nutrient Use Geographic Information System and the 2012 Census of Agriculture.

Spiegel et al. (2020) also identified four problematic manuresheds where animal source counties were sufficiently clustered to necessitate some type of manure export regime. Exports would move manure to areas that could use it from areas with excess manure available. Areas that could use imported manure are known as "sinks." The following manuresheds contained clusters of counties where animal manure nutrients needed to be transported to surrounding counties: North and South Carolina poultry and hog production, interior highlands poultry (southern Missouri to northern Louisiana and eastern Oklahoma to the Mississippi River), southern Plains (Texas Panhandle and eastern New Mexico) beef and dairy production, and Puget Sound (Washington and Oregon) dairy and poultry production (table 4). They estimated minimum transport distances to align manure sources and sinks of 91 miles for Texas Panhandle sources to more than 225 miles for Carolina sources. However, these concerns also need to take into account the environmental sensitivities of the areas. For example, the Texas Panhandle has deep aquifers, few rain events to wash manure into streams, and few waterbodies to be polluted by manure. The Puget Sound region, however, is highly populated and contains many waterbodies.

Table 4

Characteristics of manuresheds identified as locations where confined animal facilities produce more phosphorus than can be used by nearby cropping systems in 2012

Manureshed	Counties in source area	Manure in the source area[a]	Contributions of industries to total manure phosphorus (P) in the source area[b]	Requisite sink counties Average minimum transport distance from sources to requisite sinks
Carolina poultry and hog	36 counties: 23 in North Carolina 13 in South Carolina	Wet weight: 26.76 million tons Manure P: 59,411 tons Surplus manure P: 43,614 tons		297 counties: 220 with P deficit 77 with fertilizer P surplus 229 ± 87 miles
Interior high-lands poultry	55 counties: 38 in Arkansas 7 in Missouri 5 in Oklahoma 5 in Louisiana	Wet weight: 13.87 million tons Manure P: 47,223 tons Surplus manure P: 35,468 tons		74 counties: 56 with P deficit 18 with fertilizer P surplus 176 ± 76 miles
Puget Sound dairy and poultry	7 counties: All in Washington	Wet weight: 2.25 million tons Manure P: 3,743 tons Surplus Manure P: 1,795 tons		12 counties: 10 with P deficit 2 with fertilizer P surplus 111 ± 42 miles
Southern Plains beef and dairy	8 counties: 7 in Texas 1 in New Mexico	Wet weight: 9.88 million tons Manure P: 14,261 tons Surplus manure P: 5,320 tons		14 counties: 12 with P deficit 2 with fertilizer P surplus 91 ± 32 miles

NASS = National Agricultural Statistical Service.

[a] Wet weights are derived from the 2012 U.S. Census of Agriculture (USDA, NASS, 2014) and coefficients and equations from Kellogg et al. (2014). Manure phosphorus (P) and surplus manure phosphorus P are derived from NuGIS (IPNI, 2012). Estimates account for losses from collection, spillage, volatilization (nitrogen only), and denitrification (nitrogen only).

[b] Mean contribution of industry per county in the source area, derived from the 2012 U.S. Census of Agriculture (USDA, NASS, 2014) and coefficients and equations from Kellogg et al. (2014)

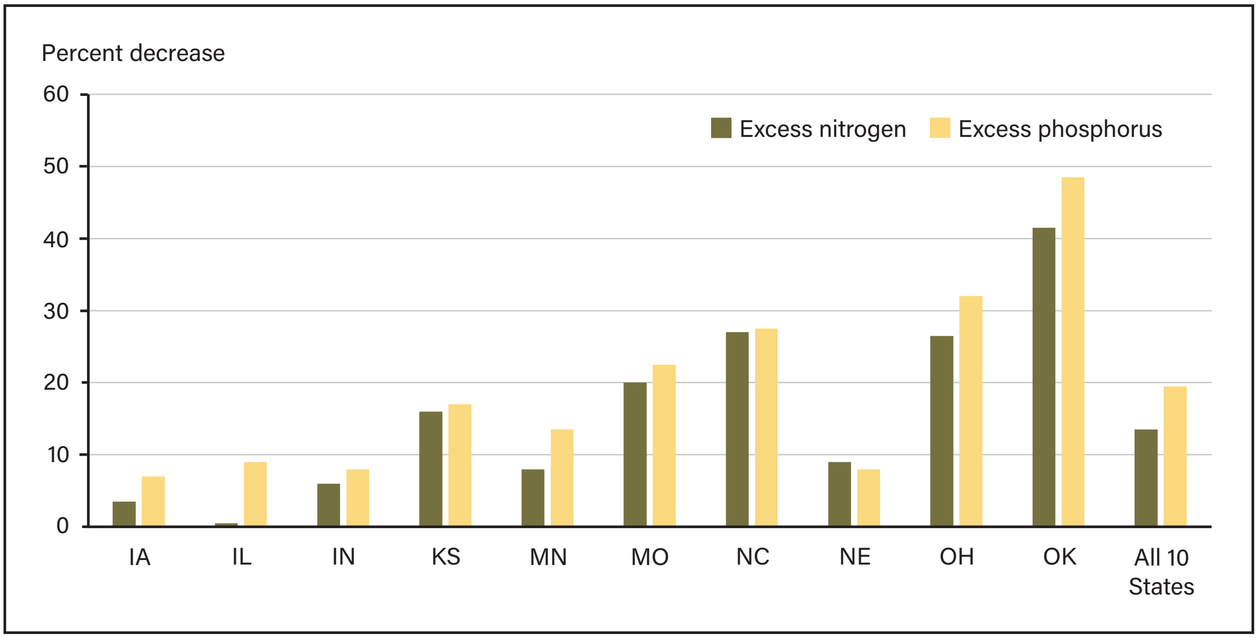
[c] Average Euclidean distance between the centroids of source counties and the centroids of requisite sink counties in each manureshed.

Source: USDA, Economic Research Service using data from 2012 U.S. Census of Agriculture (USDA, NASS, 2014) and Spiegal, S., et al.,. 2020. "Manuresheds: Advancing Nutrient Recycling in U.S. Agriculture," Agricultural Systems 182(February):102813–102813.

Gollehon et al. (2016) found that recoverable nutrients primarily originate from animal feeding operations, not pastured animals. Nehring (2020) provided data indicating that excess nutrient application in major hog-producing states declined from 2007 to 2017 (figure 12). Excess nutrient application occurs when nutrients from commercial fertilizers, manure, or both are applied at a rate greater than crop removal rates. Decreases in excess nitrogen application ranged from near zero in Illinois to more than 40 percent in Oklahoma.[8] Decreases in excess phosphorus application ranged from 6 percent in Iowa to almost 50 percent in Oklahoma. Reductions in excess manure nutrient applications are evidence that farmers are gaining more value from manure.

[8] Fertilizer prices spiked in 2008–09. This change may have caused farmers to reconsider manure value and decrease excess nutrient applications.

Figure 12
Percent decrease in excess nutrients on farms in major hog States between 2007–09 and 2015–17



Source: USDA, Economic Research Service (ERS) analysis of model estimates of excess manure nutrients based on livestock inventories, crop plantings, and yield data from USDA, ERS and USDA, National Agricultural Statistics Service, Agricultural Resource Survey, 2007–09 and 2015–17.

Ribaudo et al. (2017) defined excess nitrogen as the difference between nitrogen applied from chemical fertilizer and animal manure and the amount crops use. They estimated more than 78 percent of farms—farming 73.5 percent of harvested cropland—produce no excess nitrogen, and 10 percent of farms—farming 7 percent of harvested cropland—account for 72 percent of all excess nitrogen applications. They found farms with the following characteristics contribute a disproportionate share of excess nitrogen applications: farms with confined animals and smaller farms. However, farms in the highest excess nitrogen category applied more nitrogen from commercial fertilizer than from manure.

Critical Source Areas

Manuresheds designated as phosphorus or nitrogen sources are more at risk of environmental harm related to the excess nutrients. "Critical source areas" are those identified as contributing a disproportionately high amount to a nonpoint source pollutant. Adoption of best management practices in these areas would likely provide the highest pollution reduction per dollar spent (Pokhrel and Paudel, 2019).

Research has identified several critical source areas in the United States. Examples include:

- In the Mississippi River Basin, 33 percent of the nitrogen load from cultivated agriculture reaching the Gulf of Mexico is caused by 10 percent of cropland (White et al., 2014).
- In one New York watershed, researchers concluded that 5 percent of the watershed area produced 37 percent of the total phosphorus load (Ghebremichael et al., 2013)
- In one Vermont watershed, 18 percent of the watershed area contributed 71 percent of the total phosphorus and had a total loss rate of greater than or equal to an extreme phosphorus loss threshold of 1.8 pounds per acre (Ghebremichael et al., 2013).
- In one Pennsylvania watershed, research demonstrated that "zones of runoff production…are often a limited and identifiable portion of the landscape" (Gburek and Sharpley, 1998).
- In six priority watersheds in Oklahoma, it was found that 5 percent of the land area contributed 34 percent of the phosphorus load (Michael et al., 2009).

Government Policy

How manure is stored and handled can affect water quality, air quality, and human health. As such, some animal production facilities are subject to both State and Federal regulations. There are also State and Federal programs that provide technical and financial assistance to animal producers to help them exploit manure as a source of nutrients and energy. This section provides an overview of government policies that influence manure storage and handling. Later in the report, we discuss how government programs or policies could be used to promote the adoption of value-adding manure technologies.

Regulatory Programs

Manure can pollute water when storage structures leak or overflow and when manure runs into waterbodies during rainfall events that follow manure land application. Manure nutrients can exacerbate eutrophication of surface waters—a phenomenon caused by too many nutrients in the water, leading to algal growth and then decomposition, which reduces oxygen levels in the water below those required by aquatic organisms such as fish. Liquid manure storage structures release methane, a greenhouse gas, into the atmosphere. Because of these types of environmental concerns, Federal regulations place limitations on how certain farms can use manure. Additionally, some Federal programs incentivize farmers' use of certain manure management practices.

The U.S. Environmental Protection Agency (EPA) regulates discharge and run-off from some agricultural facilities under the Clean Water Act. Regulations aim to induce farmers to: 1) properly construct and manage manure storage structures, 2) balance land application of manure-supplied nutrients with crop uptake, and 3) choose application methods and timing to reduce field runoff. The EPA National Pollutant Discharge Elimination System (NPDES) permit program defines what animal facilities are considered point-source polluters and, hence, subject to the rule. Concentrated animal feeding operations (CAFOs) with more than 1,000 animal units,[9] and smaller farms with a history of manure pollution, are subject to EPA regulations. Additionally, specific bodies of water and their tributaries may be declared impaired and have various limitations on the use of surrounding land, depending on the source of the impairment. Normally, individual States implement the basic EPA requirements under delegated authority and may choose to expand those requirements at their own discretion, such as by reducing the size thresholds.

A patchwork of Federal and State regulations affects CAFOs of various sizes and types. The Sustainable Phosphorus Alliance (2021) reports that 13 States require NPDES permits of all large CAFOs. Eighteen states require permits of CAFOs that have or have had discharges. Table 5 summarizes the counts of States that have various animal feeding operation regulations.

[9] For regulatory purposes, 1,000 animal units would equal 1,000 head of beef cattle, 700 dairy cows, 2,500 pigs, or 30,000 broilers.

Table 5

Counts of States that have various types of CAFO[1] regulations

Regulatory question	No	Yes	Not applicable	Undetermined
All large CAFOs need NPDES[2] permit?	31	13		6
Only discharging CAFOs need NPDES permit	18	18		14
Does the State require other permits?	6	23	1	20
Are there application restrictions based on land slope?	33	16		1
Are there application restrictions within floodplains?	40	9		1
Are setbacks more restrictive than 40 CFR[3]?	14	16	9	11
Are application restrictions based on current or future rain?	28	21		1
Are there application restrictions for saturated land?	19	30		1
Are application restrictions based on snow covered or frozen ground?	15	34		1
Are application restrictions based on time of year or day?	30	19		1
Must nutrient management plans comply with NRCS Technical Standard 590[4]?	5	29	6	10
Do composition testing requirements go beyond nutrients?	24	6	6	14
Are there are maximum limits for nutrient applications?	15	15	7	13
Are manure recipients subject to same regulations?	12	14	10	14

[1]CAFO =Concentrated Animal Feeding Operation.

[2]NPDES = National Pollutant Discharge Elimination System.

[3]40 CFR is Title 40 of the Code of Federal Regulations, which regulates polluting entities; 40 CFR 412 specifies the regulations for CAFOs.

[4]NRCS Technical Standard 590 is the nutrient management standard of the USDA Natural Resource Conservation Service.

Source: Sustainable Phosphorus Alliance.

Regulations may have had unintended consequences in terms of industry structure, as producers attempt to reduce costs by avoiding regulations. Sneeringer and Key (2011) found that almost 8 percent of swine operations avoided environmental regulations by staying just under the CAFO regulatory size threshold. The authors suggested that "to create fewer distributional distortions, regulations could be phased in with the size of the operation in a continuous manner." In 2003, the EPA considered decreasing the size at which AFOs are regulated under the Clean Water Act but left the size at 1,000 animal units. There were also discussions about whether integrators should be held partially responsible for environmental damages, but that was not implemented.

Nutrient Management Plans

The nutrient management plan is central to EPA and State efforts to reduce pollution from manure and specifies the appropriate manure application rates, application times, and locations. Comprehensive nutrient management plans incorporate nutrient management plans but have additional components, such as odor management and feed management. Some State CAFO operating permits also regulate manure marketing or transportation. Many States require manure applicators to be certified.

As indicated above, comprehensive nutrient management plans are required for CAFOs, and they are also required for other animal feeding operations that receive Environmental Quality Incentives Program support from USDA (see the next section for more information about this program). In theory, nutrient management plans help farmers to use manure nutrients efficiently and reduce negative environmental impacts. Currently, all CAFOs are required to develop a comprehensive nutrient management plan, and plans must be developed by accredited personnel or farmers who have been certified. McCann (2009) found that the farmer transaction costs associated with developing comprehensive nutrient management plans exhibited economies of scale. Developing a less stringent process for smaller farmers, who are not required to obtain a nutrient management plan, may encourage them to participate in manure nutrient management planning.

Several studies have examined the farmer costs of implementing practices often outlined in nutrient management plans. Norwood and Chvosta (2005) found that North Carolina's manure application regulations for nitrogen and phosphorus rate had negative unintended consequences in terms of higher costs for farmers and potential harm to the environment. Fleming and Long (2002) found that limiting manure application to slopes less than 12 percent reduced net income by 7 percent. They concluded that the "slope restriction can be ruled inefficient only if the costs of the policy exceed the benefits," which they did not measure.

Fleming (1999) found that hog farmers could be incentivized to incorporate or inject manure if the application setback length from neighbors, municipalities, public areas, and water bodies for injected manure was sufficiently less than that for unincorporated manure.

Studies have also shown that requiring manure application based on phosphorus limits may increase manure value because it reduces the overapplication, and therefore devaluing, of nitrogen supplied by manure. However, phosphorus limits also increase the cost of manure application because it requires access to more land. Whether it increases or decreases net income depends on specific farm conditions, such as distance to fields and cropping system receiving the manure (Fleming et al., 2021). Massey and Gedikoglu (2021) found that farmers may sacrifice net income because of time constraints.

Assistance Programs

Several Federal programs influence farmers manure management decisions through financial and technical assistance, or by creating markets for manure byproducts or by permitting environmentally beneficial manure management practices. Assistance programs encourage the adoption of approved practices, which benefit both the farmer and society by reducing the cost to the farmer. Without governmental financial assistance, the direct benefit to the farmer might not cover the cost of the practice.

Environmental Quality Incentives Program

Established in the 1996 farm bill, the USDA Environmental Quality Incentives Program (EQIP) incentivizes the adoption of voluntary environmental practices on working lands. Under the 2018 farm bill, at least 50 percent of funds must be used for animal operations. Currently funded practices relating to manure include waste storage facilities, waste transfer, sediment basins, waste separation facilities, composting facilities, anaerobic digesters, and improved nutrient management. The program provides subsidies for the cost of the practices, as well as technical assistance by USDA, Natural Resource Conservation Service (NRCS) staff. The maximum amount a farmer can receive is $450,000. According to the U.S. Congressional Research Service, in fiscal year (FY) 2019, about 45 percent of valid applications were funded. They estimate the cost of the unfunded applications was $1.5 billion (Stubbs, 2020).

Renewable Energy Credits

Manure can be transformed into energy that generates credits in State and Federal renewable energy programs. The U.S. Renewable Fuel Standard, which originated with the Energy Policy Act of 2005, requires that renewable fuels be blended into transportation fuels (U.S. Department of Energy, 2021). Under the Renewable Fuel Standard program, obligated parties (refiners and importers of gasoline or diesel) achieve compliance by blending renewable fuels into transportation fuel or by obtaining credits (called Renewable Identification Numbers, or RINs).

Each gallon of renewable fuel that is produced creates a RIN. RINs are categorized according to the type of biomass used to produce the fuel, the fuel's production process, the type of fuel produced, and the estimated greenhouse gas savings associated with the renewable fuel. Manure and other cellulosic material can be used to create renewable natural gas—an advanced biofuel—or electricity (U.S. Department of Energy, 2021). Both energy forms may create RINs that have value to the holder. The value of the tradable RINs increases renewable fuel's value and thereby encourages its production. Renewable fuel generated from manure thus has value as a source of energy plus additional value from its RIN. The emerging technologies used to generate biofuel from manure are described in the second part of this report.

Manure can also be used as source of renewable fuel to satisfy carbon fuel standards. The California Air Resources Board (CARB) implemented the Low Carbon Fuel Standard (LCFS) in 2011, as one of the nine discrete early action measures to reduce California's greenhouse gas emissions (California Air Resources Board, 2021b). The LCFS policy initiatives have helped kickstart the market for renewable natural gas (RNG) and renewable electricity generated from on-farm anaerobic digesters. Oregon, Washington, and British Columbia, Canada, have strategically aligned policies with California to reduce GHGs and promote clean energy (Lipson, 2019).

The LCFS is designed to decrease the carbon intensity (CI) of California's transportation fuel pool and provide an increasing range of low-carbon and renewable alternatives to gasoline and diesel fuel, which reduce petroleum dependency and achieve air quality benefits. The CI scores are compared to a declining CI benchmark for each year, so that low carbon fuels below the benchmark generate LCFS credits, while fuels above the CI benchmark generate LCFS deficits. The LCFS credits can be monetized if the renewable energy is conveyed (via pipeline or other means) and used as a transportation fuel. Therefore, fuel can be generated in a non-LCFS state, conveyed, and later utilized in a LCFS state to obtain credits.

Carbon Cap and Trade Credits

California's greenhouse gas cap and trade program has also facilitated the installation of methane digesters in that State since 2015 (California Department of Food and Agriculture, 2021b). The trading program establishes a price signal needed to drive long-term investment in cleaner fuels and more efficient use of energy. The program is designed to provide covered entities, such as utilities and the transportation sector, the flexibility to seek out and implement the lowest cost options to reduce emissions (California Air Resources Board, 2021a). The program creates allowances equal to the total amount of permissible emissions (i.e., the cap). Each year, fewer allowances are created and the annual cap declines. Covered entities may acquire allowances through auction, limited free allocation (for eligible entities), and by trading with other entities in the program, such as animal feeding operations, which are not required to reduce emissions.

Water Quality (or Nutrient) Trading Programs

Water quality trading programs allow polluting entities with high abatement costs to pay other polluting entities with low abatement costs to create nutrient credits that they can trade, which means that the same environmental quality can be achieved at lower cost. Point-nonpoint source water quality trading has been allowed under the Clean Water Act since the 1990s.[10] In some cases, animal feeding operations can reduce nutrient emissions and then sell credits to point sources to help them meet their permit requirements at lower cost (Sneeringer, 2016). Due to manure management's nonpoint nature, program provisions must ensure reductions actually occur so that water quality goals are reached; water quality trading rules, thus, represent policy decisions. Water quality trading can entail substantial transaction costs (Fang et al., 2005). Sneeringer (2016) indicated that animal feeding operations faced greater barriers to participating in nutrient trading than crop farms, so are less likely to participate. This was especially true for operations that were not already permitted and those that did not have cropland. Sneeringer's (2016) simulation of participation by Chesapeake Bay farmers estimated that 92 percent of small animal feeding operations (AFOs) and 100 percent of large animal feeding operations that do not have excess nutrients, relative to crop requirements, would find it cost beneficial to participate in water quality trading programs offering $20 per pound of nitrogen credit. However, for those with excess nutrients, participation would range from 35 percent to 59 percent for small and large AFOs, respectively. If the trading program is for phosphorous, the maximum participation rate would be less than 4 percent. At prices below $6 per pound, participation was minimal.

The EPA reports that 39 water quality programs in 11 States allowed point source-nonpoint source trading in 2016. Of the 39 programs, 35 had active trades in 2016 (U.S. Environmental Protection Agency, 2021c). In Pennsylvania, 17 point-nonpoint source trades occurred between 2006 and 2012. Most of trades related to poultry manure exported from the Chesapeake Bay watershed. The price per pound of nitrogen per year ranged from $2.75 to $15 (Pennsylvania Department of Environmental Protection, 2012).

Labelling

Labels and certification programs can facilitate markets and improve consumer welfare by providing information on quality or other characteristics that would be difficult for consumers to determine before or even after purchase and use of the product. Such programs may also facilitate markets for goods with environmental benefits—with so-called eco-labels. For example, the USDA Organic label has increased the production of organic agricultural products and increased demand for manure as a fertilizer (Greene et al., 2009).

Economic Opportunities for Farmers

Farmers have the potential to create economic opportunities by adopting technologies and practices that maximize the value of manure produced on their farms. Fundamental to identifying the most appropriate opportunities, however, is understanding the system in which a farm operates. A farm's approach to production and the broader technological, economic, and policy context form a system with which a manure management system must align.

[10] Point sources of pollution refer to entities for which the origin of pollutants is relatively easy to identify, such as a factory or waste treatment plant with a pipe flowing into a water body. Point sources, regardless of their abatement costs, are regulated by the Clean Water Act. Nonpoint sources are those for which the source is difficult to identify, such as lawns or fields.

The sections below describe the technologies capable of increasing manure's value for farms and articulates how several key themes—benefits and costs, adoption barriers, and farm size—apply when considering manure-related economic opportunities.

- A technology's **benefits** usually include increasing profitability by increasing the value of manure components or decreasing manure management costs. Technologies also provide benefits such as manipulating manure to work well for nonfertilizer uses, creating a steady market demand for value-added manure, or reducing nutrient or greenhouse gas releases into the environment.
- For many technologies, **barriers to adoption** include high capital and operational costs and managerial complexity. These barriers affect the extent to which individual farmers adopt technologies. Adoption may require cooperative agreements among farmers who can share the capital and operating costs and managerial expertise. Some technologies that are practical in one area may not be practical in another due to no or too little insufficient demand for transformed manure or coproducts in specific locales. Regulations can also affect whether and how farms access innovative technologies that increase manure's value.
- **Farm size** may make some manure-related technologies unattainable. Usually, larger farms have access to more opportunities because they can capture **economies of scale**. On the other hand, smaller farms may be better suited to participate in certain opportunities. For example, small farms may find a niche in developing and selling end products that have limited demand. Business arrangements, such as farmer cooperatives, allow small and medium farms to access technologies that would rarely be appropriate for any one farm to employ.

Enhancing Manure's Value as a Crop Fertilizer

Several opportunities exist for farms to enhance manure's fertilizer value or to lower its cost of use.

Subsurface Application

As mentioned in the manure application section above, subsurface application conserves the most nitrogen in manure. Farmers who have a need or market for manure-supplied nitrogen can increase value by incorporation or injection.

Feed Ration Formulation

Manure is a by-product of feeding livestock. The feed consumed by animals will affect the characteristics of the manure excreted and managed by AFOs. Ration formulations change over time in response to ingredient costs and availability. Three significant feed ingredient adaptations during the past several decades include the increased use of distillers dried grains with solubles (DDGS), phytase, and synthetic amino acids. These ingredients have the potential to alter the nutrient content and value of manure.

DDGS are a co-product of ethanol production. DDGS supply in the United States grew from 12.7 million metric tons in 2006 to 33.4 million metric tons in 2020. Approximately 70 percent of DDGs are fed to livestock (McConnell, 2021). DDGS are fed to beef cattle, dairy cattle, swine, and poultry (Hoffman and Baker, 2010).

DDGS affect both the protein and phosphorus management decisions in animal diets. Total phosphorus in DDGS averages 0.7 percent as-fed—more than 2.5 times higher than corn (National Research Council, 2012). Feeding DDGS can substantially reduce inorganic phosphorus supplementation in diets. DDGS also contain about three times the crude protein of corn.

Due to its high phosphorus and crude protein content, inclusion of DDGS in animal diets can increase nitrogen and phosphorus excretion. DDGS's relatively high fiber content also can increase manure volume when fed to pigs (Shurson, 2018).

Phytase is an enzyme that, when added to non-ruminant diets, improves phosphorus digestibility. Research has shown that feeding phytase can decrease phosphorus excretion from swine (Rojas et al., 2013) and poultry (Bosch et al., 1997). USDA ARMS survey data indicated that phytase use by hog producers reached 39 percent in 2009 (Key et al., 2011). However, the survey results in Stahlman and McCann (2012) and their interviews with feed suppliers and animal scientists imply that this is an underestimate since phytase is incorporated in mineral premixes and in the feeds provided by integrators. They conclude that almost all non-ruminant diets contain phytase.

Synthetic amino acids are manufactured for use in balancing animal rations on digestible amino acid levels. The use of synthetic amino acids allows for rations that meet all the amino acid requirements of animals while minimizing total crude protein in the feed. Balancing a ration using synthetic amino acids also reduces nitrogen excretions and ammonia emissions in swine and poultry (Kebreab et al., 2016).

Feed ingredients affect both feed costs and manure value and costs. Including DDGS in animal diets generally increases the amount of protein and phosphorus fed to animals. Beef and dairy cattle fed DDGS will likely experience greater nitrogen and phosphorus excretion. The increased nutrient excretion associated with feeding DDGS is reduced or reversed when phytase and/or synthetic amino acids are added to swine and poultry rations (Shurson, 2018).

Depending on the perspective of the animal producer, having more nitrogen and phosphorous in the manure can increase its value as it meets the fertility needs of more land, or increases its cost as regulated AFOs must transport it farther and spread it on more acres.

Most rations are formulated to obtain the least-cost ration. Some research has been done to identify low-cost rations that minimize overfeeding (Castrodeza et al., 2005) or excretion (Tozer and Stokes, 2001) of nitrogen and phosphorus. These extensions of ration formulation programs all assume that excreted nutrients have a negative value. Research incorporating the potential positive value of nutrient rich manure could not be found. The fact that crop producers pay for and use manure as a fertilizer (e.g., Ali, et al., 2012) indicates that at least some manure has sufficient value to be marketed. Ration formulation that is targeted for specific animal and cropping situations to minimize feed costs while maximizing net manure value might discover economic opportunities, particularly for use in organic crop production.

Manure Additives

By adding compounds to manure, farms can increase the end product's fertilizer value and save time and cost in fertilizer application. These additives may include nitrogen, alum, acid, biochar, and clay. Because manure has a nitrogen-to-phosphorus ratio that does not meet most crops' nitrogen-to-phosphorus removal levels, increasing manure's nitrogen level or decreasing its phosphorus level would potentially increase its overall value.

Nitrogen Amendment

Most slurry manure, especially after being stored at least 6 months, has a relatively low nitrogen-to-phosphorus ratio because ammonia volatilizes during storage, while phosphorus does not. The nutrient imbalance can decrease overall manure nutrient values because the slurry manure itself cannot meet crop nutrient needs. Thus, farms choose to supplement manure applications with chemical fertilizers and incur added application costs and field workdays.

A field trial successfully added the chemical fertilizer urea ammonium nitrate to both pig and dairy manure in Ohio (Arnold, 2020). The additions were designed to achieve specific nitrogen goals on a per acre basis, though no yield comparisons were reported. Adding the fertilizer to the manure prior to land application reduced the need for a supplemental nitrogen fertilizer application—reducing the total cost of crop fertilization.

Alum

Alum can successfully increase nitrogen and enhance phosphorus content in poultry litter, which contains bedding, excreta, feathers, etc., from the house floor. Also known as aluminum sulfate, alum is added to poultry house bedding before introducing birds and between flocks (Moore et al., 2004). Its addition reduces phosphorus losses in runoff from field-applied litter and decreases ammonia emissions within poultry houses. By reducing ammonia emissions, the litter's nitrogen component increases. Chemicals containing iron, aluminum, and calcium can also be used for phosphorus amelioration in litter (Anderson et al., 2020; Codling et al., 2000), but they do not reduce ammonia emissions (Moore et al., 1999). Other litter amendments can be used to reduce ammonia emissions: aluminum chloride, sodium bisulfate, fly ash, gypsum, zeolite, biochar, and phosphoric acid. Many of these chemicals, however, do not control phosphorus losses. Alum accomplishes both.

In a process called phosphorus-fixation, phosphorus in poultry manure chemically reacts with alum. It changes the phosphorus from water-soluble to water-insoluble forms (Moore and Miller, 1994; Shreve et al., 1995; Warren et al., 2008). The fixed-phosphorus in alum-treated litter reduces runoff loss and acts as a slow-release fertilizer. Essentially, this means the phosphorus becomes bioavailable over time (Penn and Zhang, 2017). Moore and Edwards (2007) contended that lower bioavailable phosphorus levels change litter's "effective" nitrogen-to-phosphorus ratio from 2:1 to closer to 8:1 in the application year.

In addition to phosphorus-fixation, alum decreases nitrogen losses from litter. Alum acidifies litter, which favors the formation of ammonium, a nonvolatile form of nitrogen, rather than ammonia, a volatile form of nitrogen. This change in nitrogen form provides environmental and production benefits. Studies of alum use in barns have found improved feed conversion and weight gain (Moore et al., 2000) and decreased propane and electricity usage from reductions in ventilation necessary to counteract ammonia levels (Moore et al., 1999). Lastly, as less nitrogen is lost through ammonia emissions, alum-amended litter had significantly greater total nitrogen than control litter (Sims and Luka-McCafferty, 2002).

Amending litter with alum has been practiced for several decades. However, due in part to integrated poultry production's proprietary nature, it is difficult to ascertain to what extent farms use this practice. An estimated 1 billion broilers were raised on alum-amended litter in 2011 (Moore, 2011). In comparison, roughly 9 billion U.S. broilers were produced in 2011 (MacDonald, 2014). Research shows positive net benefits to integrators and growers, and some States have alum cost-share options under the Natural Resources Conservation Service Environmental Quality Incentives Program Practice 591 (U.S. Department of Agriculture, Natural Resources Conservation Service, n.d.).

The cost of alum more than doubled between 1999 and 2016. This caused alum to move from very cost effective to marginally cost effective. The cost increase led to research showing alum mud litter amendment (AMLA, a mixture of alum mud with bauxite and sulfuric acid) was less expensive and as effective as alum itself (Anderson et al., 2020).

Because the majority of poultry production is vertically integrated, increasing adoption of alum use will primarily depend on the integrator companies, not individual farmers. Similarly, Stahlman and McCann (2012) found decisions about incorporating phytase in nonruminant (poultry and swine) diets in the Midwest were generally made by integrators or feed companies, not farmers.

Acidification

Acid is added to manure slurry collected from pig and dairy facilities to reduce ammonia emissions. Acidifying manure alters the relative acid content, favoring nonvolatile ammonium over highly volatile ammonia. Various studies have demonstrated substantial ammonia emission reductions for acidified pig slurry (40 percent to 80 percent) and cattle slurry (15 percent to 80 percent) (Fangueiro et al., 2015).

The ammonia emissions reduction depends on many factors, including acidifying method and acidifying agent. Three arrangements are most common: in-house acidification, storage tank acidification, and static-mixer acidification. Timing of acid treatment to slurry can occur just before field application or many months earlier. If it occurs many months earlier, then re-acidification may be required (Fangueiro et al., 2015).

Sulfuric acid is the most common strong acid, but hydrochloric and nitric acid have also been tested. Alternative acidifying agents have been tested but are in a more nascent development stage. These agents include: base precipitating salts, such as aluminum chloride, and fermenting materials (Fangueiro et al., 2015).

By treating manure with acid, farmers can capture benefits, including reduced in-house ammonia emissions and increased nitrogen content of manure, which may increase its fertilizer value. Research findings indicate higher levels of nitrogen in acid-treated manure compared to unacidified manure. In a study by Sørensen and Eriksen (2009), the mineral plant available nitrogen for acidified manure was 39 percent to 63 percent greater in acidified cattle slurry and 74 percent to 100 percent greater in pig slurry when it was band-applied. Kai et al. (2008) found the plant available nitrogen was on average 43 percent greater for acidified slurry compared to untreated slurry.

Environmental benefits include reduced greenhouse gas emissions. Acidification also, however, has been found to increase the labile phosphorus fraction in manure. This feature may increase yields when manure is applied to grain and forage crops, but it has potential negative environmental consequences if it increases phosphorus leaching and runoff (Fangueiro et al., 2015).

In addition to acid and infrastructure costs, producers also have to weigh the human health risks involved with using and storing large quantities of strong acids. In the case where sulfuric acid is used as the acidifying agent, hydrogen sulfide is another safety hazard. Foaming of manure in the mixing tank can also be problematic (Fangueiro et al., 2015).

Composting

During composting, manure—with or without animal bedding and other organic matter—undergoes a low-moisture digestion process that can increase its value. This biological process requires bacteria to stabilize manure's organic matter and nutrients. It shares similarities with anaerobic digestion in that it reduces the overall volume of manure, bedding, and other organic matter, and it reduces the number of pathogens. Composting's aerobic nature makes it simpler and less expensive than anaerobic digestion, though organic carbon is lost as carbon dioxide rather than being collected as methane.

Not only does composting present a low-tech management practice to improve manure's value as a soil amendment and fertilizer, but it also reduces the potential for air and water pollution (Modderman, 2019). USDA ARMS data indicate that about 5 percent of manure-fertilized cropland receives composted manure.

To compost manure, farms must manage aeration, moisture content, and additive supplements:

- **Aeration:** Aerating compost effectively reduces foul-smelling and potentially hazardous gasses such as hydrogen sulfide. Additionally, aerobic organisms produce heat, which kills pathogens such as fecal coliform and reduces viability of weed seeds in the compost. Therefore, finished compost has greater value as a fertilizer and soil amendment (Eghball and Lesoing, 2000).
- **Moisture management:** Ideally, moisture content will range from 40 percent to 60 percent by weight. A lower moisture content will limit bacterial growth and slow the composting process. A higher moisture content will prevent aeration and result in an anaerobic process.
- **Supplements:** Additive materials for compost can change the finished compost's physical and chemical properties and value. Typically, these supplements consist of carbon-rich materials, such as bedding, woodchips, sawdust, plant waste, and even cardboard. They balance manure's nutrient ratios, which may be high in nitrogen and phosphorous relative to carbon. Adding carbon becomes particularly important if introducing higher life forms (e.g., worms, larvae) to the composting process. In especially wet manure—for example, manure produced by pigs and dairies—carbon-rich additives often provide bulk to facilitate aeration (Bernal et al., 2009). Bulking materials include wood shavings, wood chips, rice straw, wheat straw, clay, and biochar (either from bamboo or other wood products). With the exception of clay, these additives are renewable resources and commonly found as byproducts of other agricultural products (Modderman, 2019).

Windrow Composting

With windrow composting, farms create elongated piles of manure and other organic matter and turn them occasionally to promote aeration. Aeration increases the composting process' speed and reduces unpleasant odors and off-gassing. This process degrades manure into stable humus. Windrows typically are placed on dedicated areas that are easy to access and minimize runoff risks. The windrow method can be done with minimal specialized equipment and expertise, making it accessible to farms of different sizes (Russelle et al., 2007). Specialized compost machinery allows for more efficient management of the windrows.

Windrows can be 3 feet to 6 feet high to allow for aeration. Windrows can be aerated passively or actively. Passive aeration uses mechanical equipment, such as tractors or front-end loaders, to turn the windrows periodically (Hay et al., 1991), or more specialized compost turners are available. Physically turning the piles would enhance aeration and proper mixing. Active aeration involves a pressurized system that blows or draws air through perforated piles. The system provides fresh oxygen and removes noxious gasses (Sweeten and Auvermann, 2008).

High-Rate Composting

High-rate composting typically occurs in drums rotated about their axis for mixing and aeration. Drums can be as small as 55 gallons or measure as big as 10 feet in diameter and 100 feet long. The larger drums are capable of processing 50 tons at a time (Misra et al., 2003).

A high-rate composting system expedites the composting process. It reduces time required to compost manure, typically 4 to 8 weeks, to as little as 1 to 7 days. This is accomplished by maintaining optimal levels of temperature, moisture, aeration, pH, and nutrient ratios. This system's disadvantage is its added costs for specialized equipment, oversight, and electricity.

To take advantage of economies of scale, a cooperative was created by several contract poultry producers in central Missouri about 15 years ago. The co-op bought a drum composter (Ward, 2016). The time required to produce finished compost is about 3 days to 4 days, and the producers sell—and in some cases, apply—the compost to neighboring farms in bulk. The initial business model included a bagging component for retail sales that is no longer in operation.

Compost Bedded Pack Barns

Compost bedded pack barns are an example of a production system that integrates manure management into milk production to improve value. Compost bedded pack barns are specifically designed to compost manure in and among dairy cows' bedding, which is different than reusing fiber for bedding because the manure treatment is occurring in the barn with the cows. Compost barn benefits include improved cow comfort and cleanliness, low construction costs, reduced operational complexity due to less wastewater and lagoon management, and less odors (Bewley and Black, 2012).

For compost bedding, farmers use sawdust or fine wood shavings for bedding in a large, open area (Bewley and Black, 2012). Materials with larger particle sizes, such as straw and cedar chips, are not as desirable as sawdust because those materials tend to be more difficult to properly aerate, or they—particularly cedar—may have properties that inhibit bacterial activity necessary for composting (Janni et al., 2007).

Bedding is replaced at 6- to 12-month intervals (Barberg et al., 2007). It must be aerated daily, generally using common farm equipment.

Janni et al. (2007) and Barberg et al. (2007) revealed that dairies in Minnesota using composting barns had herd sizes between 38 to 177 head; herd size averaged 77. For a herd of 75 milking cows, about 15.5 tons of bedding are added to the barn every 2 to 5 weeks between cleanouts in order to add carbon, reduce moisture, and replace material degraded through composting (Janni et al., 2007). Studies have suggested that the added comfort and resulting cow health benefits can outweigh the added bedding cost in terms of milk production and quality (Leso et al., 2020).

In one study, up to 30 percent of manure was scrapped from the concrete pad adjacent to the feeding lane and stored for a short time before being blended with the composted bedding and undergoing land application. The compost from dairy beds can improve soil organic matter content but is not as effective a fertilizer as liquid manure in terms of nutrient content or availability (Leso et al., 2020). Farms may need to supplement land-applied bedding with additional fertilizer, particularly if the crop has a high nitrogen demand.

Bedding material (e.g., sawdust) costs can significantly affect this system's economic viability. Several farms design compost barns so they can be converted to scraped freestall systems if needed due to changes in bedding costs and availability.

Vermicomposting

Vermicomposting refers to a process whereby worms are fed raw manure, digested manure, composted manure, or a combination of these with other low-value feedstocks—such as office paper, cardboard, or vegetation and fruit waste. The worms reduce overall organic matter and produce new worms and worm "castings" (i.e., worm manure). Castings are a high-value, organic fertilizer (Taiwo and Otoo, 2013).

Although vermicomposting has been applied to multiple types of agricultural manure, it is best suited for "dry" manure (e.g., beef manure, poultry litter, horse bedding) due to optimal moisture content of the substrate being 75 percent to 85 percent (Lorimor et al., 2006). Conventional vermicomposting processes have three distinct designs: batch, semicontinuous, and continuous. The three systems differ in terms of their infrastructure costs and time to produce finished vermicompost. Batch systems offer lower cost but have at least a 6-month cycle. Continuous systems are more expensive but provide a cycle as short as 30 days (Lorimor et al., 2006).

Vermicomposting disadvantages are primarily twofold. First, the manure entering the system may need to have its nutrient ratio and moisture content adjusted prior to vermicomposting. Poultry manure in particular—due to its relatively high nitrogen-to-carbon ratio—generally requires added organic material, such as paper or cardboard, in a 4-to-1 ratio to achieve successful vermicomposting (Hamilton et al., 2008). The second disadvantage is the space needed for worm beds. Some have reported an application rate of 1.25 centimeters per day of fresh manure (Lorimor et al., 2006). A dairy cow that weighs 1,300 pounds will produce approximately 16 gallons of manure per day (Chastain and Camberato, 2004). At an application of 1.25 centimeters per day, each dairy cow would require 52 square feet of worm bed each day. A herd of 100 dairy cows would require 5,200 square feet, and a herd of 1,000 cows would require a plot the size of a football field. The facility would likely require a roof and temperature control. Studies have noted that adding bacteria to the vermicomposting system can reduce the overall treatment time and increase organic reduction (Nova Pinedo et al., 2019).

Other challenges associated with vermicomposting include the operator receiving training to manage worm health. The operator must monitor factors such as pH, temperature, and pests and predators. Additionally, the vermicomposting operation would need a business plan specific to selling the compost, high-value castings fertilizer, and worms themselves.

Larvae-Based Composting

In larvae-based composting, the insect larvae feed on manure, grow, and are harvested prior to metamorphosis. Two streams of value stem from this process. First, the larvae essentially break down manure as they feed on it. Second, the larvae themselves can create valuable products. They secrete waste void of pathogens—much like worms do in vermicomposting—and this waste is considered a high-value compost. Some work has explored further processing the harvested larvae into value-added products. For example, some businesses have packaged dried black soldier fly larvae (1-pound to 50-pound bags) and sold it as feed supplements and treats for chickens and pets.

Insect larvae-based treatment occurs best when raw manure is introduced directly to larvae, typically placed below animals. Several species of insect larvae have been used for composting manure, and many types of fly larvae can reduce manure's organic content. Only the black soldier fly, however, is not considered a pest (Lorimor et al., 2006).

The black soldier fly's manure decomposition potential has some variability—likely due to manure composition and environmental factors. One study demonstrated black soldier flies reduce swine waste by 39 percent, chicken waste by 50 percent, and a mix of chicken and cow waste by 25 percent (S. Kumar et al., 2018).

Disadvantages of black soldier fly treatment include treatment system size, need for customized infrastructure to allow raw manure to be conveyed to the black soldier fly beds as soon as possible, and the cost of heating the beds. Additionally, farm operators that choose a larvae-based composting system require new training to manage larvae health. They must know how to balance pH, temperature, pests, predators, and other factors. They also need an additional business plan and technical knowledge to produce and sell value-added products.

Black soldier fly treatment may yield several potential commercially viable byproducts. Larvae grown on manure can be used as an animal feedstuff. One study showed that black soldier flies could supplement up to 25 percent of fish diets without a decline in growth rate (Kumar et al., 2018). Black soldier fly larvae can be collected and dried. Grease from the larvae can be extracted and refined to make biodiesel. The post-extraction black soldier fly larvae that remain can be used as feedstuff. Lastly, the processed manure (i.e., droppings from the black soldier fly larvae) can be hydrolyzed into a type of sugar used for industrial processes such as ethanol fermentation (Li et al., 2011).

Additive Supplements for Composting

Several studies have focused on understanding how additives affect compost. Huang et al. (2006b) examined the transformation of organic matter when co-composting pig manure with sawdust as an additive. Key findings were that the carbon-to-nitrogen ratio decreased over time; the lowest carbon-to-nitrogen ratio occurred after 63 days of compost (Huang et al., 2006a). In compost, nitrogen is the most valuable nutrient for crop application, so the lower carbon-to-nitrogen ratio makes the compost more valuable per unit of volume.

Biochar has been used as a compost additive. Made from burned agricultural byproducts such as wood or bamboo, biochar added to compost affects the compost's microbial community and resulting chemical composition. The changes depend on the type of manure being composted. A study of biochar compost found that the presence of biochar is associated with lower nitrous oxide—a strong greenhouse gas linked to climate change—emissions due to modification of the type of bacteria in the compost (Jindo et al., 2012; C. Wang et al., 2013).

Another study examined the greenhouse gases emitted during composting with clay additives and chicken manure. Various clay-to-chicken manure ratios were tested. The results found that clay additives promoted decomposition, helped compost retain nitrogen (and therefore, reduced nitrogen gas emissions), and produced less odor compared to chicken manure without clay additives. Clay additives also produced a chemically stable finished compost in a shorter time period than when composting chicken manure alone (H. Chen et al., 2018).

Materials added to compost can also affect the product's value. These relatively simple applications can be cost-effective for small-scale producers and those with integrated crop and animal systems (Russelle et al., 2007). Additives, combined with best practices for manure composting, represent an opportunity for small operations to improve the efficiency of their resources.

Liquid-Solids Separation

For liquid manure systems, a first step to use other technologies may be to separate the liquid fraction. Liquid-solids separation technologies provide several benefits and functions for high moisture manure management typical of swine and dairy operations that utilize lagoons for storage and/or treatment of process water. These technologies are used to remove coarse solids from flush dairy water, separate fine solids for nutrient recovery, reduce the moisture content in solids to make them more suitable for other processes, and even remove particles so small that the water becomes potable. Coarse solids can be used as a soil amendment to increase organic content or modified into a value-added product discussed later in this report. The bulk of nutrients are found in the fine solids. Fertilizers developed using these solids can be more valuable, particularly if additives are used to adjust nutrient ratios.

Farmers may choose to implement mechanical screens (e.g., rotary drums, slope screens) or nonmechanical screens (e.g., weeping walls, baffled sedimentation basins) to minimize the amount of solid material entering the lagoon. By keeping solids from entering the lagoon, the lagoon has greater capacity to hold liquid, and farms can reduce costs related to removing solids from the lagoon. As an added benefit, screens remove nutrients to some degree—estimated to be 5 percent of nitrogen and phosphorous for mechanical screens versus 10 percent of nitrogen and 18 percent of phosphorous for a two-stage weeping wall (Meyer et al., 2007; Mukhtar et al., 2011). Many of these simple technologies are generally affordable at approximately $40,000 for a 120-head dairy farm. They could be considered as a viable first step toward better manure management and, perhaps as importantly, toward a system that better manages nutrients.

Centrifuge, filtration, and dissolved air flotation technologies separate fine solids from liquid. Presses are used for dewatering both coarse fiber and fine solids and in some cases are the only system used when recycling fiber for animal bedding. Drying reduces moisture content after dewatering and may be the only pre-treatment process for poultry, which have a naturally dry manure. Both dewatering and/or drying are used to ease handling and transportation of manure solids and are generally needed to prepare manure for value-added processing opportunities, such as energy generation and fiber products manufacturing.

Centrifuges

Centrifuges have reduced moisture content in solids, or slurry, for 90 years (U.S. Environmental Protection Agency, 2000c). In a centrifuge system, a liquid-solids slurry, typically with 3 percent to 10 percent solids content, is introduced to a tube that spins at high speeds to separate solids from liquid. An internal auger conveys the separated solids to a discharge port, and liquid is collected and discharged at the other end of the tube. The separated solids discharged from the centrifuge typically have a solids content of 18 percent to 26 percent (Sprick, 2017).

A dewatering centrifuge performs somewhat comparably to a belt press, screw press, or multidisc press. Like these other technologies, the centrifuge's effectiveness depends highly on polymer selection and dosing rate, if applicable. Polymers are chemicals added to increase aggregates and enhance solid–liquid separation. Material is pre-screened to remove sand, if present, and sometimes coarse solids from the slurry stream prior to using the centrifuge. Additional solids or nutrient capture is possible when using micro, ultra, or nanofiltration of the liquid effluent. Centrifuges have been noted to remove particles that conventional cloth filtration and microfiltration would screen (Cooney, 2005).

Centrifuges have the potential to increase solids content by more than 20 percent compared with belt presses and screw presses. However, the power needed to operate these technologies varies greatly. The centrifuge requires 10 times more power than the screw or belt presses (Sprick, 2017). Maintenance costs and management, plus adding and managing polymer, represent other challenges associated with using a centrifuge to separate solids and liquid.

Filtration

Through filtration, slurry manure passes through or over a medium to remove some constituent of manure. Physical filtration occurs when the water portion passes through the membrane, and particles are rejected based on their size. A driving force must be present in physical filtration to get the water to flow through the membrane. Smaller membrane pores result in smaller particles being retained. Maintaining the filter's integrity is critical. Filters that are fouled (i.e., clogged) or torn can reduce operational capacity or water quality until they are repaired.

Filters become fouled over time. To eliminate some of the fouling, they can be backwashed or scoured. Periodic chemical cleaning helps to extend the filter's life, but every chemical cleaning reclaims less and less active filter each time (The MBR Site, 2020). Energy use increases as the filter fouls. It and pressure gradient determine the filter's efficiency and operational state and also determine when the membrane is reaching the end of its useful life, which has ranged from 6 years to 13 years for municipal applications (Cote et al., 2012). Filters are often staged from coarse to fine in order to reduce fouling on the finer filters.

Filters have many types of membranes and pore sizes. Marketing and industrial secrets can sometimes make it difficult to discern what type and pore size is being used in a specific system. A cloth-type membrane is not technically a membrane, but it can do a good job of removing particles, especially when polymer is added prior to filtration. A few feet of hydraulic head are usually all the energy that is needed to drive water through a cloth filter, which can filter particles down to the size of milled flour and many bacteria—about one micron. This is generally referred to as "particle filtration."

Vacuum drum filters have recently been applied to swine and flush dairy manure. The technology uses diatomaceous earth as a filter medium and has a knife that scrapes the solids from the rotating vacuum drum as it becomes clogged. This technology has been used in the textile industry for several decades.

Microfiltration, ultrafiltration, and nanofiltration can be accomplished by thermoplastic-type, ceramic, or metal membranes. They require a pump or pumps to generate the necessary driving force, and each type—from micro to nano—requires progressively greater energy to operate. "Microfiltration can remove particles down to 0.1 microns (all bacteria), ultrafiltration down to 0.01 microns (75 percent of viruses), and nanofiltration down to 0.01 microns (all viruses, most herbicides and insecticides)" (Osmonics, Inc., 2012). Note, reverse osmosis is even finer. Often discussed separately from filtration, it relies on salt concentration and pressure gradients as a molecular driving force rather than a simple vacuum. Such systems demineralize water because even dissolved salts are removed.

A couple of notable advancements in animal manure filtration have occurred in the past few years. These include metal membranes and vibrating membranes. Thermoplastic membranes can tear after extended use or if the pressure becomes too high. "Providers of municipal systems offer membrane warranties that range from 3-10 years," which allows for inferring the expected membrane life in a setting that can be considered less harsh than agricultural service (U.S. Environmental Protection Agency, 2007). At least two companies have begun to offer a titanium and stainless-steel membrane to extend operational life. These products are new to the market, and the level of filtration they achieve is not clear. Vibrating membranes are offered by at least one company. The vibrating membrane prevents fouling and allows for longer membrane life. This technology, too, is in its infancy, and its effectiveness is unclear.

Dissolved Air Floatation

Dissolved air floatation, a solids-liquid separation process, has existed for more than 50 years (Ross et al., 2000). Typically used in industries where wastewater streams have high fat, oil, or grease concentrations, dissolved air floatation systems use microbubbles to increase the buoyancy of particles in water. A dissolved air floatation system's performance highly depends on how well the solids float. Before using dissolved air floatation systems, operators should encourage particles to flocculate (i.e., form clumps) to achieve greater floatability. Flocculation occurs in a tank where dosing pumps add flocculant at a rate that depends on the type of solids and flowrate through the system.

In a manure context, polymer is added to slurry prior to dissolved air floatation to encourage an increase in particle size. Once in the dissolved air floatation system, particles attach to the microbubbles, float to the surface, and form a floating sludge layer. They are then skimmed off the top with a set of moving baffles known as rake assembly flights (Tchobanoglous et al., 2003). The sludge produced by the dissolved air floatation system is generally dewatered using a low-sheer technology, so the flocs (i.e., particle clumps) remain intact.

Agricultural producers may choose from many types of flocculant made by many different manufacturers. Commercial flocculants are designed and calibrated to bind specific types of solids. A system designed around a specific flocculant brand or type may require recalibrating if the flocculant type changes. Also, the specific application requires customized polymer dosages and airflow.

Note, the authors investigated two dissolved air floatation system installations at Indiana dairy farms. Results of that investigation are available for download as a University of Missouri Extension case study (Canter et al., 2021).

Presses

As dewatering technologies, presses apply direct pressure to solids to squeeze out residual moisture. The most common types include belt presses, filter presses, screw presses, and moving ring presses. Each of these technologies differs slightly in the way in which it applies pressure to remove water. However, most require preflocculation for dewatering of fine solids.

- **Belt presses:** Also known as belt filter presses, this type of press conveys the solids on belts, with small perforations, through a series of rollers that apply increasing pressures. The belt, or belts, are wound through the rollers in a way that the belts press the solids. Water is squeezed through the perforations, and the solids remain on the belt.
- **Filter presses:** This type of press—also called a frame filter press or recessed-plate filter press—uses a series of filter bags or hammocks on a rack or bar. Slurry is inserted into the bags, which are compressed along the rack using low mechanical pressure followed by higher hydraulic pressure. Water is squeezed out of the bags, the system decompresses the bags, and the solids are dumped from the bags onto a conveyor.
- **Screw presses and moving ring or moving disc presses:** These two presses are similar. The solids move through a cylinder using an auger. The pressure within the cylinder is controlled by a restriction plate on the solids discharge end of the auger. The solids are pressed against either a perforated cylinder (screw press) or a series of tightly spaced rings that slightly oscillate back and forth (moving ring press) as they move from the inlet to the outlet. The screw press has fewer moving parts and may be less expensive than the moving ring press, but the moving ring press is less likely to clog than the screw press (Canter et al., 2021).

These dewatering technologies can begin to process slurry once it has a solids content higher than 3 percent. The end product is called cake, and its consistency and quality vary depending on the manure feedstock's attributes and the technology's capabilities, not just in terms of technology type but by the effectiveness of the other equipment packaged and integrated as part of the overall manure management process. In general, these technologies will produce a cake with a solids content of 30 percent to 50 percent (U.S. Environmental Protection Agency, 2000b; 2000a). Reducing the liquid content in manure by 90 percent has benefits including decreased weight, easier transportation because it can be stacked in a pile, and decreased electrical input needed for further drying required before further processing such as combustion or pelletizing.

A minimal solids content of 3 percent means that presses can be used to directly dewater some forms of manure. As an example, screw presses have successfully dewatered scraped dairy manure to be recycled as bedding without drying or digestion. This type of application can be successful if only large fibers are to be recovered. Similarly, presses have been used successfully without polymer addition to dewater fiber once the fiber has been screened from digestate or flush-type dairies. Polymer addition, as noted above, is needed for capturing and dewatering of fine solids and nutrient removal. A high level of control and monitoring is needed for polymer addition if the feedstock has variable characteristics, which can be greatly reduced using a digestor to homogenize the manure (U.S. Environmental Protection Agency, 2000a). Additionally, presses are generally part of a larger process, not a standalone solution. Thus, the system must be implemented to produce benefits.

Drying

Manure dryers typically use heated air to reduce manure's moisture content, concentrate its nutrients, reduce ammonia and other emissions, and kill pathogens. The amount of energy needed to dry manure to an 85 percent to 95 percent dry matter content depends highly on the manure feedstock's moisture content and the prevailing climate in the region. Energy costs are potentially high, however. Drying has been a popular option for poultry litter because it has low initial moisture content—reported to be 21 percent to 45 percent across 8 farms (Chastain et al., 2004) It is beginning to be more widely adopted in the dairy and swine industries. However, for these industries to dry manure, the manure requires a pretreatment to reduce the moisture content from the initial 83 percent to 90 percent seen in these types of operations (ASABE, 2019).

Poultry growers, especially layer houses, often utilize drying technologies to manage ammonia emissions and fly populations. Various innovative approaches have focused on reducing drying time or energy use to improve overall efficiency. One company uses perforated steel plates to increase warm air circulation ("OptiPlate: High Capacity Steel Plate Manure Drying System," n.d.). Another company integrates the drying system with the poultry house to utilize the heat produced (i.e., ventilation exhaust air) by the birds to help dry the manure. This saves energy (VDL Adgrtotech, n.d.). These drying technologies do not necessarily reduce ammonia in the litter or recover ammonia being emitted. Reducing moisture content is an effective way of reducing litter's biological activity that can generate ammonia and, thus, conserving more nitrogen in the final fertilizer product. Nitrogen lost via emissions or evaporation represents a challenge tied to drying manure.

Applying conventional drying technology to dairy manure can be split into two categories: bedding recovery and manure drying. Bedding recovery refers to using solids-liquid separation to isolate the larger fiber before drying it in a rotary drum dryer to be reused or combusted for power or heat generation (Farm Show Magazine, 2008). The heat can be used to help scrub the water of ammonia, but this system is not designed to conserve manure nutrients. The drying can pay for itself in reduced hauling cost and bedding recovery. An innovative technology on the market does recover a significant percentage of nutrients from dairy manure. It uses a novel thickener that operates similar to an Archimedes Screw, or screw pump/conveyor, which is simply a screw-shaped surface inside a pipe used primarily to propel dry bulk materials. The rotating plates lift solids from a slurry that are dried via warm air to roughly 88 percent moisture content. "The solids then enter a conveyor belt dryer where moisture is reduced to 15 percent (85 percent dry matter). A nutrient recovery wash system can be installed to capture dust and ammonia in the rejected air from the belt dryer. Nutrient recovery has been reported to be greater than 90 percent with the wash system. The drying system alone has been reported to recover 20 percent nitrogen, 50 percent phosphorous, and 25 percent potassium" (Hallbar Consulting, n.d.).

Farms in Texas and Washington have implemented a developing drying technology, though its performance and cost have not yet been made available. The system is similar to conventional drying as it reduces moisture content to create dry, stackable solids. It is unique in that it captures the steam from the drying process, compresses it, and recycles it to help heat the drying bed. The compressed stream that enters the drying system leaves as saturated liquid and is distilled while ammonia is removed. This creates streams of aqueous ammonia and clean water ("Varcor System," n.d.). The technology provider claims a zero-nutrient-discharge farm is possible.

The swine industry appears to have had limited application of manure drying technology. One company reports using drying technology for solids management from a biological treatment process that includes coarse screening, aerobic digestion, flocculation, and filtration. Waste sludge is mixed with dry matter recovered from the coarse screening to create a feedstock with a moisture content of 82 percent to 84 percent. The feedstock is fed through multiple dryers to create a finished product with a 13 percent to 15 percent moisture content (Deutsch, 2007). While the drying component of this system is considered a high-rate drying technique known as “biodrying,” this overall system is unique in that it utilizes aerobic digestion to reduce the mass of solids sent to the dryer (Avalos Ramirez et al., 2012).

A new development for swine and presumably small flush dairies is passive solids drying. The patent, published in July 2020, describes a system that uses a constructed wetland for drying manure solids (Phasey, 2020). A standard lagoon collects manure and manages water. The liquid supernatant is land-applied, and the solids are dredged and sent to a constructed wetland with a sand and gravel underdrain system. Water that seeps through the substrate is pumped back to the lagoon. Evapotranspiration from the wetland plants and evaporation from the wetland surface dry the solids. The technology is on few facilities and performance and economic information is not readily available.

Pelletizing

Pelletizing converts raw or composted manure into a more consistent, denser product. This process conserves most of the original nutrients, improves storage and handling, and reduces transportation costs. Because pellets can be less costly to distribute than raw manure, they may allow for redistributing manure nutrients from areas with excess nutrients to areas with too little nutrients. Also, compared with raw manure, pellets offer several other benefits. Those include reducing farms’ reliance on synthetic fertilizers, potentially modifying the manure’s nutrient levels and composition to meet specific crop needs, and better controlling nutrient application in the field (Hao and He, 2019).

Converting animal manure into pellets involves drying the manure if needed, homogenizing or crushing it, screening it, pelletizing it, cooling, and storing those pellets (Hao and He, 2020). Pellet makers may choose to produce extruded or granulated pellets. To make extruded pellets, facilities use pressure agglomeration to create cylindrical pellets. Granulated pellets are often created with a rotating disk (Prasai et al., 2018), and they are less dense round pellets. Round granules can spread more uniformly when applied as fertilizer (Prasai et al., 2018). Given the processing equipment needed, pelletizing is not a farm-scale technology.

Several variables affect pellet quality and the process’ production costs: the manure source and its moisture content, pelletizing methods (e.g., extruded, granulated, die and roller), supplements added (e.g., binding agents, mineral and synthetic fertilizers, ash, other organic materials), pellet size and density, and intended pellet use (Hao and He, 2019). Poultry litter is the most commonly used input to make pellets. Interest is growing in pelletizing cattle, hog, and horse manure or compost.

Adding supplements while pelletizing manure allows the producer to modify the pellet’s nutrient levels and composition to meet specific crop needs and gain greater control over field application (Hao and He, 2019). Binders can improve pellets’ nutrient content and other physical characteristics such as moisture content, density, size, and nutrient release rate. Research evaluated mixing ash and poultry manure to produce granulated fertilizers, and it concluded that the ash content increased granule strength but also increased energy consumption (Mieldažys et al., 2019).

Pound for pound, pelletized manure is a low-value fertilizer compared with chemical alternatives. However, niche markets (such as certified organic production) represent a major market for pelleted manure. According to a strengths, weaknesses, opportunities, and threats analysis of organic wastes suitable for fertilizer—animal manure represented the major source of organic waste used in agriculture. Organic manure fertilizers improved soil physical and chemical properties and provided nutrients (Mieldažys et al., 2016). Pelleted manure was found to improve storage, transport, spreading, and insertion into soil. Improved storage addresses a major problem with using manure as a crop fertilizer. That is, manure production typically continues throughout the year, but land application is seasonal.

Pelleted manure needs to be applied to soils earlier than mineral fertilizers and raw animal manure. The earlier application allows sufficient time for mineralization and release of nutrients for subsequent crop uptake. Nitrous oxide emissions may increase with the use of pellets (Hao and He, 2019).

Research has studied a pilot-scale process for making granulated organic- and organo-mineral fertilizers using poultry manure. It explored the effects of manure's moisture content, energy consumption, and the possibility to obtain nutrient-balanced fertilizers (Mazeika et al., 2016). Poultry manure was extruded with and without additional diammonium phosphate and potassium chloride. Significant increases in rapeseed and potato yields were observed with both the organic and enhanced fertilizers. Another research project compared the response of greenhouse-grown cucumber production under no fertilization, conventional liquid fertilizer treatments, pelleted organic turkey litter-based compost, and pelleted organic dairy manure vermicompost (Y. Li and Mattson, 2019). The study concluded that the organic fertilizer combination can be substituted for conventional fertilizer and has no negative effect on cucumber seed germination, seedling survival, seedling height, and leaf greenness.

Other research compared pelleted, composted turkey litter with crushed walnut shells, pelletized soybean meal, and corncob grit on weed control (Carlson et al., 2020). The organic materials were used as part of an air-propelled abrasive grits system used to control in-row weeds for organic production. A greenhouse study followed to determine growth responses of wheat, kale, and velvetleaf in soils amended with these grits. The study concluded that applying organic pelleted, composted turkey litter as air-propelled grit may improve crop growth, and grits with high carbon-to-nitrogen ratios may immobilize soil-available nitrogen without affecting plant growth (Carlson et al., 2020).

To successfully pelletize manure, firms require a proper business environment and very limited documentation has shared success stories of manure-based pelletizing businesses. During spring 2019, Dr. Teng Lim visited a commercial organic fertilizer company in Minnesota. Strategically located near many large turkey farms, the company began operating in 1980. It specializes in aerobically composted turkey litter, and it pelletizes the composted litter into organic fertilizers. Another example is the Perdue AgriRecycle joint venture that was making a product called MicroStart 60® produced in Seaford, Delaware (Lichtenberg et al., 2002). The $13 million plant was designed with a capacity of 150,000 tons of pellets per year but was restricted to 80,000 tons per year due to regulations on truck traffic. The plant collected litter from poultry houses within a 75-mile radius, paying $4 per ton to clean the chicken houses and an average of $10 per ton in transportation to the plant. They projected a pellet sale price of $55 per ton would be needed to remain viable, but it is not clear how subsidies from the States of Delaware and Maryland affected that calculation. As of 2008, the facility was approaching the maximum capacity limited by traffic regulation (MacDonald, 2008).

The owner stressed the importance of securing organic certification and establishing a name brand. One significant challenge is securing U.S. State certifications, which is a time-consuming process. The owner found it can be easier to obtain certification in many foreign countries and shipping composted manure pellets to foreign countries can be less expensive than shipping to certain U.S. States. The certification label assures that the product contains a USDA-verified amount of renewable biological ingredients and is listed as allowable for use in certified organic farming by the Organic Materials Review Institute. Developing fertilizers with certified amounts of nitrogen, phosphorus, and potassium values, and/or formulated and coated to guarantee slower nitrogen releases have opened markets with nurseries and high-value greenhouse operations.

Effective manure pelleting requires time to obtain organic certification, establish a name brand, and innovate niche products to meet different market needs.

Recent Developments in Manure Fertilizer Technologies

Processing manure components into value-added fertilizers represents another opportunity for farmers. Two recent commercially-viable approaches—vermifiltration and struvite production—add value to water present in manure systems.

Vermifiltration

Traditional vermicomposting requires manure to have a relatively low moisture content. A nonconventional system called vermifiltration (Lorimor et al., 2006) treats process water from manure systems (i.e., a waste stream that has had solids removed). It operates like a traditional trickling filter where water is allowed to flow over a substrate (e.g., rocks, plastic) and a bacterial biofilm degrades pollutants. One vermifiltration system in particular uses wood chips as a substrate to support bacterial growth and provide a carbon source for worm growth (Fuentes, 2009). In this system, the bacteria consume dissolved nutrients and pollutants in the water, and the worms consume the bacteria that slough off the upper layers and drop to the bottom of the system. The wood chips, along with worm waste or "castings," are periodically harvested and turned into commercially viable fertilizer.

Unlike vermicomposting, vermifiltration has the added advantage of treating the liquid waste stream by reducing and removing dissolved constituents (particularly ammonia) via bacterial degradation. It also promotes adsorption of some materials onto the fresh organic material (i.e., wood chips) periodically added to promote healthy worm growth.

Challenges associated with vermifiltration include caring for the worms and identifying secondary product markets that produce the appropriate return on investment.

Struvite

A crystalized mineral compound (composed of magnesium, ammonium, and phosphate), struvite has long been considered a nuisance in municipal wastewater treatment plants because it tends to form in pipes and pumps. Some dairy farms have reported similar crystal accumulation issues. Research has focused on developing reactors that would grow struvite crystals while removing nitrogen and phosphorus from liquid manure. The struvite crystals could be harvested from the reactors and used as fertilizer.

Struvite forms when phosphate, ammonium, and magnesium mix at a pH between 7 and 11 (Buchanan et al., 1994). A struvite crystallizer design, consisting of a cone-shaped fluidized bed, was tested at both laboratory and field scales to remove phosphorus from a swine lagoon (Bowers and Westerman, 2005). Magnesium was supplemented and pH was controlled, and the total phosphorus removal was as high as 56 percent and 80 percent for the lab and field tests, respectively. In another earlier study, forced precipitation of struvite was conducted using swine manure and anaerobically digested manure, magnesium oxide was added, and the manure was heated to 35°C (Beal et al., 1999). The study reported to 98 percent of the reactive phosphorus (PO43-) was removed. Recent evaluation of the technology has suggested that "between 22 percent and 36 percent of the total phosphorous releases from the agricultural sector, including manure releases and fertilizer application, can be achieved if the technology is applied to cattle operations alone" (Martín-Hernández et al., 2020).

Considerable research has addressed how to commercialize a system that effectively produces struvite from water high in phosphate and ammonium. Only one type of configuration, the up-flow fluidized bed reactor has demonstrated the ability to achieve commercial success. The reactor introduces a contaminated water flow to the bottom of the system, along with feed lines for chemical addition. The bottom portion of the reactor is constantly stirred to make sure homogenous conditions and chemical reactions. The "bed" comprises struvite crystals, which must be added as a substrate to seed the reactor. Treating manure with acid outside the reactor can increase phosphorus capture in the form of struvite (Reindl, 2007). To generate a commercially viable amount of struvite, the system must be carefully monitored to maintain a target pH and proper ammonium, phosphate, and magnesium ratios. Washington State University has ongoing research into a mobile struvite generator to test the viability of farms sharing an up-flow fluidized bed reactor (Washington State University, 2020). Detailed results and economic feasibility for long-term, large-scale on-farm operation are not yet available. A cone-shaped crystallizer system was tested in the field and operated with direct pumping of covered digester liquid at a flow rate of 1.43 gallons/minute, and the tests were conducted 40 times, each of a 2-hour duration during September 2007 to October 2008 (Westerman et al., 2010). Reductions of total phosphorus averaged 55 ± 10 percent (mean ± standard deviation). Costs and returns were estimated for a 1,000-sow farrow-to-finish operation, and it was estimated to be $0.66 per hundredweight of live hog marketed.

If producing struvite, operational costs represent the largest barrier to adoption—particularly costs incurred to add magnesium. The Manure Production and Characteristics Standards, D384.2, documented phosphorous production per animal per day to range from 0.17 pounds for lactating cows to 0.00048 pounds for layer hens (ASABE, 2019). Magnesium production, on the other hand, is negligible. The magnesium required for struvite production ranges from 0.26 to 0.5 pounds per animal per day for lactating cows—1.5 times to 3 times the mass of phosphorous generated. This suggests the need to add magnesium at the dairy farm for long-term struvite production, which may represent a significant operational cost.

Nonfertilizer Manure Uses

Manure has potential uses other than fertilizer. Prior to manure becoming a valuable input into nonfertilizer uses, it may need to undergo first-stage processing. Ultimately, the processed manure may work well in applications, including energy production, and as animal bedding or growth substrate.

Energy Production

Manure has historically been used for heating, cooking, and even building primitive shelters. New technologies can convert manure into forms that can be harvested for energy development. Other technologies can directly convert manure into heat, energy, or biogas. Larvae-based composting, discussed in the composting section, is one such technology. Another technology involves algae.

Algae

Algae treatment can provide value-added benefits via biofuel production, fertilizer, or supplemental animal foodstuff (R. Chen et al., 2012). Algae treatment refers to growing and harvesting algae as a means to improve water quality or the composition of raw manure or anaerobic digestion discharges. Algae assimilate nitrogen and phosphorous as it grows, so it removes those nutrients from water. As photosynthesis occurs, carbon is also sequestered.

High-rate algal pond systems have been studied for treating swine and dairy manure (Mulbry et al., 2005). Bioenergy production on dairy farms via algae could increase overall bioenergy production by 64 percent, compared with U.S. anaerobic digesters (Chowdhury and Freire, 2015). Moreover, algae could be considered superior to other energy crops due to biomass yield, biodiesel volume produced from an equivalent weight, heating value, and lost opportunity cost to grow terrestrial food crops (K. Kumar et al., 2015). As a slow-release fertilizer, algae has been noted as effective as a commercial fertilizer, in terms of nitrogen and phosphorous supply to cucumber and corn crops in a 20-day period (Mulbry et al., 2005).

Note, some studies have suggested that bioenergy end products should be tailored to the manure systems used. Swine waste has high nitrogen concentrations, and it produces algae high in carbohydrates. Algae high in carbohydrates are more suited for ethanol fermentation, and algae high in lipids are needed for biodiesel. Therefore, ethanol should be the end product to increase bioenergy recovery, though most studies have focused on biodiesel production potential (Wang et al., 2015).

Treating algae and producing related value-added products require three major steps: cultivation, harvesting, and dewatering or drying. Cultivation occurs in closed or open systems. Closed systems, known as "photobioreactors," are essentially transparent tubes or plates. Open systems are open to the environment. They include big shallow ponds, tanks, circular ponds, and raceway ponds. Of these four, raceway ponds are noted to hold the most promise for large-scale applications in terms of biomass generation and operating cost (Kumar et al., 2015; Ranga Rao et al., 2012).

Open and closed systems vary by productivity (i.e., algae yield), size, and cost. Photobioreactors can be up to 10 times as productive. However, based on gas exchange requirements, photobioreactors are limited to a surface area of roughly 100 square meters, whereas open pond systems can scale to 10,000 square meters or more (Kumar et al. 2015). Commercial photobioreactor costs can be up to 100 times higher than costs for open pond systems as well (Kumar et al., 2015). Note, costs referenced by Kumar et al. (2015) are specifically for the cultivation technology. Fasaei et al. (2018) suggest that photobioreactors can be cost-competitive if the added harvesting and dewatering or drying costs are considered. The key difference is the labor cost for harvesting and energy for dewatering. Fasaei et al. (2018) acknowledge that overall open system costs can be significantly reduced by investing in automation to reduce labor inputs. Open systems are less expensive to install for equivalent amounts of throughput and have demonstrated commercial viability for algae cultivation (Zhang et al., 2013).

The algal turf scrubber is somewhat of a hybrid with open and closed features. It allows nutrient-laden water to flow down a channel that has a mat or some other growth substrate. The algae grows on the mat, which provides optimal sunlight and allows for easier harvest (Zhang et al., 2013).

As another cultivation factor, algae growth depends highly on temperature. Seasonal temperature variation in the United States restricts year-round outdoor algae cultivation in almost all States. This significantly reduces economic viability (Chowdhury and Freire, 2015). The cultivation step most determines algae production's economics, but harvesting and dewatering technologies affect overall process efficiency.

Harvesting and dewatering steps represent up to 50 percent of operational costs and 90 percent of related equipment costs (Sahoo et al., 2017). The goal is to reduce algae's moisture content to create a total solids content of 10 percent to 25 percent prior to processing. Technologies commonly used include centrifugation, spiral plate technology, pressure filtration, vacuum filtration, flocculation or sedimentation, drum drying, spray drying, and solar drying. Literature on low-cost or optimal configuration provides no clear direction. One study noted the low-cost combination to consist of pressure filtration, followed by centrifugation (Fasaei et al., 2018). Another study suggested pressure filtration followed by solar drying to minimize cost (Sahoo et al., 2017). Note, open cultivation systems produce algae with roughly 0.06 percent dry matter, and closed cultivation systems produce algae with roughly 0.35 percent dry matter. As a result, closed systems result in much lower operational and energy costs for harvesting and dewatering (Fasaei et al., 2018). Thus, properly pairing the cultivation system with the harvesting and dewatering system affects overall economics.

Harvesting and dewatering may require one or more mechanical technologies to achieve the necessary consistency for further processing. Notably high in labor and energy, they have been reported as the primary inhibiting factor in making algae energetically favorable (Chowdhury and Freire, 2015).

With respect to barriers and management problems, algae treatment has a high-level infrastructure need to support the overall system. For example, pretreating manure or digestate is required to reduce turbidity (i.e., increase clarity) to allow for sunlight to penetrate the water column, or high organic loading may inhibit algae's nutrient uptake. Pretreatment could include filtration; coagulation, flocculation or clarification; or dilution (Wang et al., 2015; Chen et al., 2012).

Last, consider the operational challenge of coordinating the various processes and technologies needed to create value-added products from dried algae. Biodiesel production, ethanol fermentation, pelletization and granulation, pyrolysis, gasification, and biochar formation all require specific technologies that require additional capital and operational resources. The 64-percent increase in bioenergy production by including algae over a simple anaerobic digestion system—as noted above—is only possible by combining nearly all the aforementioned technologies, as well as side-stream recovery and nutrient conversion. Algae inclusion, with biodiesel and pyrolysis for biochar production alone, increases bioenergy production over anaerobic digestion alone by only 16 percent (Chowdhury and Freire, 2015).

Anaerobic Digesters and Biogas Purifiers

Anaerobic digestion's (AD) popularity for agricultural applications stems in large part from its potential to produce renewable energy by facilitating the growth of microbes, which convert organic carbon to capturable methane while reducing greenhouse gas emissions emitted from livestock manure. The anaerobic process turns manure and other organic wastes into a more consistent product (digestate) and reduces the potential contamination of waterways (Key and Sneeringer, 2011a). The biogas produced by AD consists primarily of methane (about 50 percent to 75 percent) and carbon dioxide (about 25 percent to 50 percent). It also contains trace amounts of water vapor, nitrogen, hydrogen sulfide, and oxygen (Scarlat et al., 2018). Biogas can be used as a substitute for any application designed for natural gas. One of the simplest applications of biogas, which requires little to no additional processing, is burning the gas onsite to generate heat or electricity for localized use or sale. Additionally, a purification system can be installed to remove impurities such as moisture, hydrogen sulfide, and other undesirable gasses (Haren and Fleming, 2005). Biogas purification increases the value by creating a product that is comparable to natural gas, termed renewable natural gas (RNG). RNG can be injected into pipelines and used at large-scale electrical plants or as fuel for vehicles. Thus, on-farm operations have considerable flexibility to increase biogas' value (Anderson et al., 2013).

Digestate, the semisolid residue that remains after digestion, has nutrient content that is similar to that of the feedstock manure and can still be used as fertilizer or other value-added products (Scarlat et al., 2018). The nitrogen and phosphate reduction in manure digestate during AD is minimal. Applying digestate as a crop fertilizer is the most economical option; this approach allows for using the digestate's nutrients and reducing chemical fertilizer costs (Campos et al., 2019). Digestate lacks a uniform nutrient composition, however. Its composition depends on the origin of material, and its application may have varying effects on crop yields and growth (Pelaez-Samaniego et al., 2017). Furthermore, nutrients preserved in the digestate may have different levels and ratios of plant-available nutrients (Möller and Müller, 2012). Table C.1 in Appendix C shares average values of major properties and microelement contents to show how liquid digestates can differ.

Digesters are airtight, heated containers. They have the following fundamental components: 1) a premixing tank or designated area to dilute slurry if needed, 2) a digester vessel or vessels that facilitate the biological breakdown of organic inputs, 3) a system for collecting biogas, and 4) a system for collecting and reusing effluent and solid residues (Ackrill and Abdo, 2020). Anaerobic digestion technology demands little energy for heating and electricity under normal conditions, so it is a highly energy-efficient process (Li et al., 2016). Other commonly recognized on-farm AD benefits include odor reduction, air quality improvement, greenhouse gas emissions reduction, reduction in potential pathogens from manure entering waterways, and the use of the digestate as an alternative to chemical fertilizers (Chen and Neibling, 2014).

The U.S. Environmental Protection Agency outlined seven broad types of digesters in its 2011 guide, Recovering Value from Waste (AgSTAR, 2011). The following discussion summarizes each technology's general characteristics and extent of adoption:

- **Covered Lagoon:** Categorized as a passive system, covered lagoons add biogas recovery to an existing treatment component. The covered lagoon, when compared to other anaerobic digester types, requires relatively low maintenance and serves as a storage and a treatment system. This design has two cells. The first is covered, and its fluid levels remain constant to promote manure breakdown. The second is uncovered, and fluid levels fluctuate—serving as storage of digestate. Temperatures in the digester fluctuate with the seasons. Consequently, gas production fluctuates (Hamilton, 2019). The covered lagoon represents roughly 25 percent of on-farm anaerobic digesters reported in the AgSTAR database as of September 2020. Roughly 50 percent of those were in California (U.S. Environmental Protection Agency, 2021d).

- **Complete Mix Digester:** These systems are categorized as "low rate." Manure flowing through the digester is the main source of methane-forming microorganisms (Hamilton, 2019). These systems feature a tank where manure is often heated and mixed with microorganisms. Liquids remain in the digester for 10 to 25 days while treatment volume is typically maintained. Mixing can be continuous or intermittent. The complete mix design is the most widely used on-farm anaerobic digester in the United States. In 2020, 91 complete mix digesters were under construction or operating—roughly 32 percent of all digesters, as reported by AgSTAR (U.S. Environmental Protection Agency, 2021d).

- **Plug Flow Digester:** Also considered a low-rate system, plug flow digesters have contents that generally flow through in batches and do not require mechanical mixing like a complete mix digester. Typically shaped as a rectangle, this system has a 15- to 20-day recommended retention time (Hamilton, 2019).

- **Fixed Film:** Often characterized as a high-rate system, fixed film digesters have methane-forming microorganisms trapped in the digester to increase efficiency. The fixed film system is a heated tank that contains media, such as wood chips or plastic rings, on which bacteria can attach and grow (AgSTAR, 2011). Manure is passed through the media and digested by the growing bacteria. Fixed film digesters provide a relatively short retention time: 2 to 6 days. They can be relatively small compared with other digester types; however, the added media increases the likelihood of potential clogging within the reactor. Clogging would reduce potential biogas production (Chen and Neibling, 2014).

- **Anaerobic Sequencing Batch Reactors:** Also classified as a high-rate system, this system often has a heated tank and collects gas at the top. Waste is added and removed from the system in batches. This system is well-suited for diluted manures (L. Chen and Neibling, 2014)

- **High Solids Fermentation:** These heated, airtight tanks digest high-solids manure (AgSTAR, 2011). In addition to manure, other organic substances—such as grass, food waste, and biodiesel byproducts—are added to the digester.

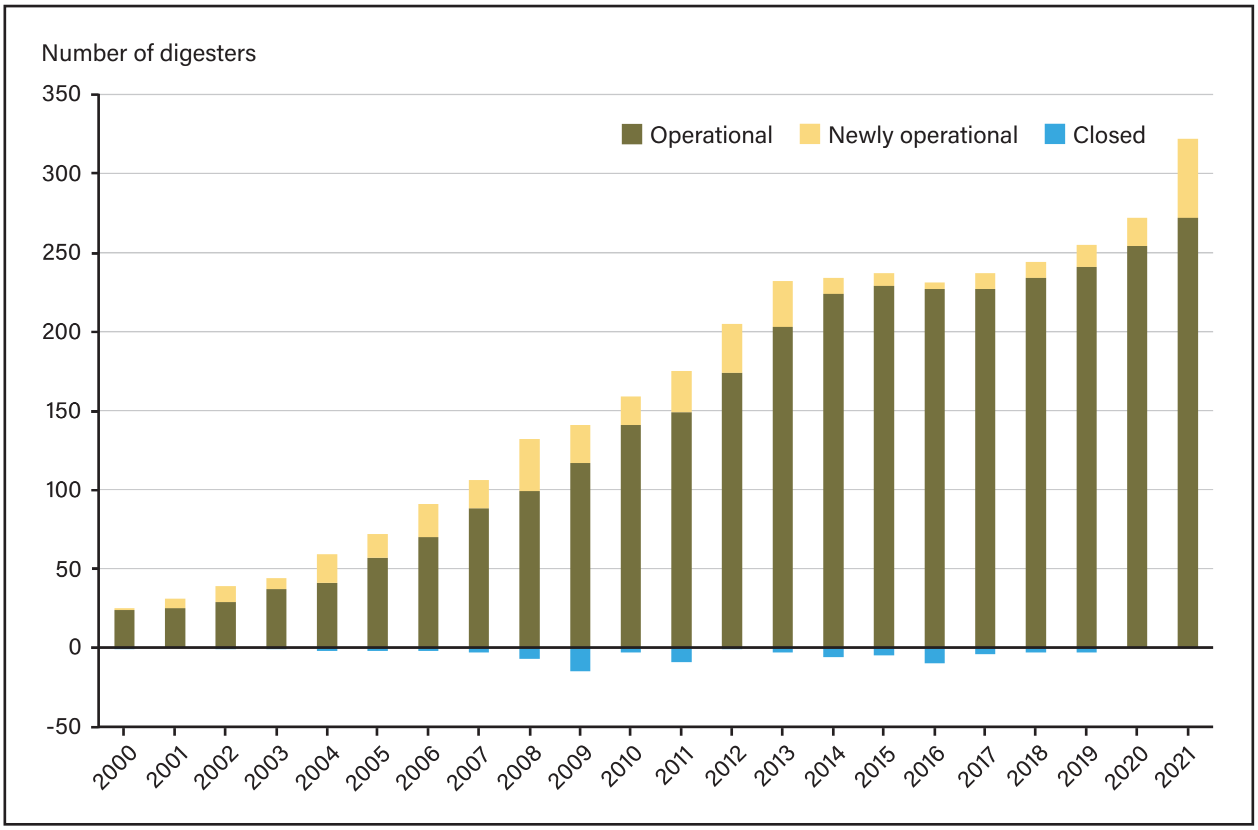
- **Up-Flow Anaerobic Sludge Blanket (UASB):** A high-rate system, up-flow anaerobic sludge blankets have influent constantly added to the base of the vertical tank. Bacteria are suspended in the reactor. Powar et al. (2013) found the UASB reactor to be highly applicable treatment to a broad range of industrial wastewater sources, including dairy wastewater. Factors that significantly affect a UASB reactor's performance and stability include influent pH (between 6.3–7.8); mixing achieved through biomass or slurry recirculation or mechanical mixers; and hydraulic retention time.

Anaerobic digesters require constant maintenance and supervision to maintain the temperatures, consistency, and pH levels needed for digestion. Potential hazards associated with anaerobic digestion systems are leakage, explosion, asphyxiation, and hydrogen sulfide poisoning. Trained operators must provide supervision to prevent and mitigate potential risks. Additionally, hydrogen sulfide produced during digestion can corrode systems and must be removed to keep digesters properly maintained and operational (Labatut and Gooch, 2012).

Current State of the Market

AgSTAR data shows the number of onfarm anaerobic digester systems steadily increased during the past several decades (figure 13). A total of 322 systems were operational at the end of 2021, including 50 that started operating that year. Although adoption began in the 1970s, steady growth of onfarm anaerobic digestion systems in the United States did not pick up until the 1990s. Growth then persisted until about 2013, after which it slowed considerably. In 2016, facility closures outnumbered new entrants 10 to 4 (figure 14). Reasons cited in 2016 for facility closures in the AgSTAR database—if they were cited at all—include high operational costs, odor complaints, and mechanical issues. Recently, the number of digesters increased again, as shown in figure 13. This increase can be explained in large part by the renewable energy policies in California discussed above.

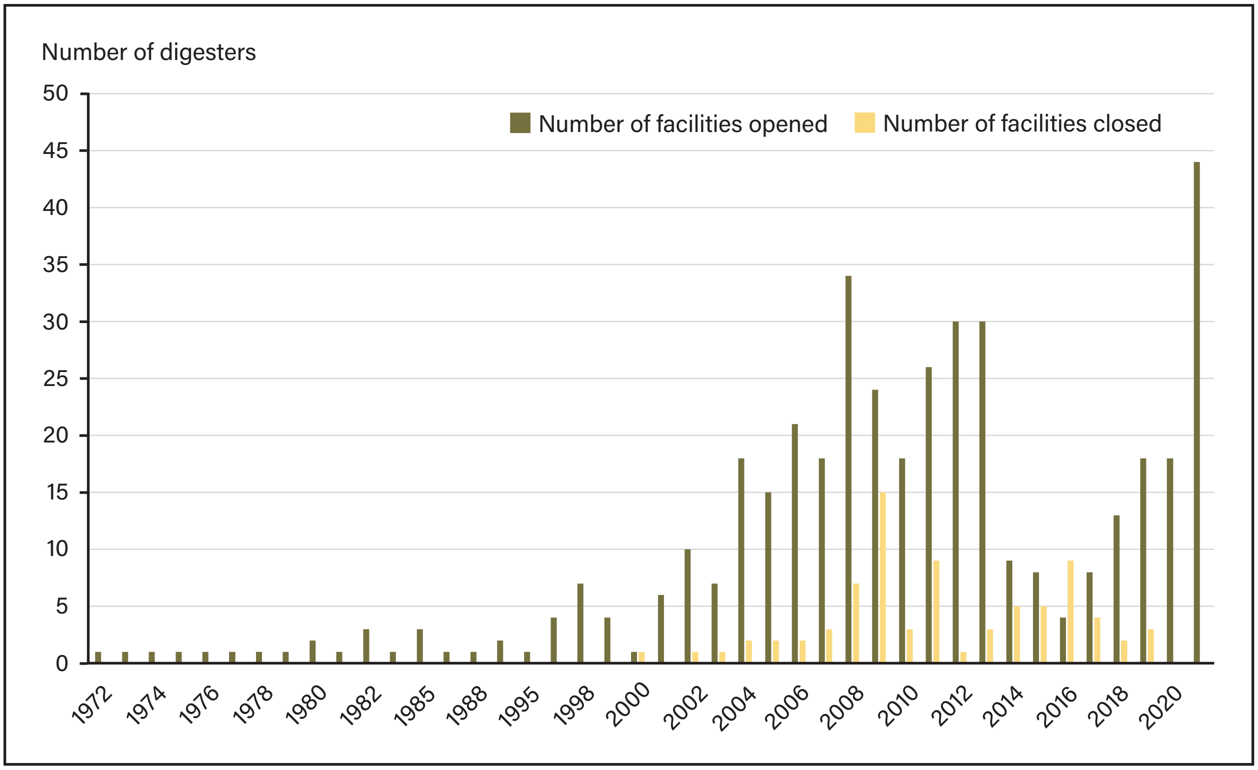
Figure 13
On-farm anaerobic digester systems in the United States



Source: U.S. Environmental Protection Agency, AgSTAR Database.

Figure 14

Number of on-farm anaerobic digesters opened and closed in the United States, by year



Source: U.S. Environmental Protection Agency, AgSTAR Database.

Roughly 78 percent of all on-farm anaerobic digestion facilities in the United States are found on dairies. The annual percentage change of dairy cows on farms with anaerobic digesters increased every year except for 1 in the past 30 years (U.S. Environmental Protection Agency, 2021d).

Anaerobic digester adoption has not been uniform across all States. Regional differences in climate, State government support, incentives, and agriculture production including type and scale can influence adoption rates significantly. Methane production in California, Wisconsin, and Pennsylvania have the highest adoption rates (U.S. Environmental Protection Agency, 2021d).

Biogas produced by anaerobic digesters can be refined by removing impurities—including moisture, carbon dioxide, hydrogen sulfide—and compressed to produce renewable natural gas. In 2011, nearly all on-farm anaerobic digestion projects operating in the United States were providing renewable natural gas to generate electricity off-site. With the renewable transportation fuels market fostered by Federal and State rules and incentives, 76 percent of renewable natural gas projects were diverting renewable natural gas into transportation fuels. Only 24 percent generated electricity off-site in 2017 (Escudero, 2017). Using renewable natural gas to generate electricity is less efficient when compared with other renewable natural gas uses. The two main renewable natural gas uses are injection into a pipeline or onsite or local applications (e.g., onsite vehicle fueling station, transport by truck) (EPA, 2020). Onsite renewable natural gas vehicle fuel projects avoid the need to meet natural gas pipeline specifications, and they avoid the costs incurred to transport renewable natural gas to an existing pipeline and connect with it. Onsite use requires adequate, consistent demand for renewable natural gas vehicle fuel. Examples include a fleet of milk or feed delivery trucks. Matching fleet demand to the renewable natural gas source can be problematic in some rural areas, as larger fleets are generally located in urban centers.

As mentioned in the Renewable Energy Credits section of this report, the California Air Resources Board (CARB) implemented the Low Carbon Fuel Standard (LCFS) program to encourage the use of cleaner low-carbon transportation fuels and therefore, reduce GHG emissions and decrease petroleum dependence in the transportation sector (California Air Resources Board, 2021b). The LCFS standards are expressed in terms of the CI (Carbon Intensity) where diesel's adjusted CI is 100 grams of carbon dioxide equivalent per megajoule of energy and all other fuel alternatives are relative to diesel. In a spreadsheet of Current Fuel Pathways, CARB provides data on 54 dairy and swine facilities producing natural gas. The certified CI for these fuels generated from manure feedstock ranged from -151 to -532 with an average of -317 (Note: These certified CIs are relative to the diesel CI of 100) (California Air Resources Board, 2021).

Since May 2018, the weekly average price of LCFS credits has traded between $150 to $211/mt (metric ton). The CARB assigned dairy manure CI score of -250 gCO_2e/MJ provides significant incentives to install anaerobic digesters that create renewable natural gas. LCFS credits trading for $198/ton translate into a price of $50/MMBtu (Metric Million British thermal units) (Greene, 2019), or more than 12 times the EIA forecast 2022 pipeline price of fossil natural gas of $4/cubic foot (Energy Information Administration, 2022).

Though many U.S. farms could use anaerobic digesters, the technology is somewhat limited to larger operations—those with at least 500 cows—due to relatively high capital cost per animal for smaller facilities (Wang et al., 2021). A 2017 study found the initial investment was approximately $1.35 million for small to medium-sized Vermont farms with 75 cows to 500 cows, and costs were $2.44 million for large farms with more than 500 cows. The initial investment averaged $2.03 million (Wang et al., 2017). On-farm anaerobic digestion systems are financially infeasible for most dairies. Growth in anaerobic digester use has occurred because of grant and subsidy support from governmental agencies and organizations. Even with subsidized support to offset initial capital investments, small to mid-sized dairy farms lack the economies of scale needed to generate a positive return on investment.

Incentives and Support

As detailed in the section on Government Assistance Programs, Renewable Energy Credits in the form of RINS and California LCFS credits are major incentives driving the use of anaerobic digesters to create renewable energy. Other incentives also exist that assist farmers adding value to manure.

The USDA offers value-added producer grants for anaerobic digester projects (USDA, RD, 2019). Many on-farm, animal manure-based anaerobic digesters were developed with State and Federal incentives. For example, the California Department of Food and Agriculture offers a Dairy Digester Research and Development Program, which provides financial assistance to install dairy digesters in California to reduce greenhouse gas emissions (California Department of Food and Agriculture, 2021b). Table 6 summarizes the annual number of projects, funds awarded, matching funds, and total project costs. Funded projects grew from 6 in 2015 to 43 in 2019, and total funding increased from $11.1 million to $67.4 million. The necessary matching funds ranged from 1.4 times to 2.5 times of the awarded funding—suggesting the industry is committed to making such investments and expecting the projects to be profitable. As mentioned above, there are also policy instruments in California that enable farmers to generate renewable energy credits from manure.

Table 6
Summary of California Dairy Digester Research and Development Program funded projects, 2015–19

Year	Number of projects	Total	Match	Project total
2015	6	$11,091,526	$28,071,744	$39,163,270
2017	16	$30,750,000	$74,047,964	$104,797,964
2018	42	$72,409,276	$101,879,089	$174,288,365
2019	43	$67,393,550	$166,653,623	$234,047,173

Source: USDA, Economic Research Service using data from California Department of Food and Agriculture, Dairy Digester Research and Development Program.

The California Department of Food and Agriculture data on biogas projects reinforces that biogas is becoming popular for use as vehicle fuel or injecting into major compressed natural gas pipelines, not generating electricity. The annual reports indicated all six projects in 2015 were designed to generate electricity, but no electricity-generation projects in 2017 and 2018 received funding. Only 2 of the 43 projects planned are for electricity generation. In addition, most, if not all, funded projects used covered lagoons to produce biogas. In general, the funding needed to install covered-lagoon digesters is lower than costs for anaerobic digesters such as complete-mix and plug-flow systems.

In California, the Alternative Manure Management Program provides an example of a State incentive program meant to help many on-farm manure solid separation projects (California Department of Food and Agriculture, 2021a). The program provides financial assistance needed to implement non-digester manure management practices, which will result in reduced greenhouse gas emissions. Table 7 summarizes the grants provided and match in place for different manure management improvement projects. The total number of projects funded increased from 13 in 2017 to 38 and 50 projects in 2018 and 2019, respectively. The farmer match decreased from 2017 to 2019.

Guaranteed loans are another funding mechanism for digesters and biogas systems. USDA offers Rural Energy for America Program (REAP) Renewable Energy Systems & Energy Efficiency Improvement Guaranteed Loans & Grants (U.S. Department of Agriculture, Rural Development, 2020). REAP helps farmers, rural small businesses, and agricultural producers build renewable energy systems or make energy efficiency improvements by providing loan guarantees on loans up to 75 percent of total project costs and grant funding for up to 25 percent of total project costs. For example, "In Magnolia, N.C., Optima KV received a $6.5 million loan guarantee for an anaerobic digester that will help hog producers dispose of waste by converting it to energy. The project aggregates multiple biogas streams at a refinery. The resulting natural gas is then transported via pipeline to a power plant to generate electricity" (U.S. Department of Agriculture, 2019). The USDA EQIP Program can also be applied to receive financial and technical assistance to implement structural and management conservation practices that optimize environmental benefits. Please see EQIP information in the Federal Program section of this report.

Table 7
Summary of California Department of Food and Agriculture manure management program funding for 2017–19

Type	Project number	Total	Match
2017			
Flush-to-scrape	5	$3,174,726	$248,839
Solid separation	6	$2,782,166	$365,248
Compost bedded pack barn	2	$1,499,746	$1,395,995
Total	13	$7,456,638	$2,010,082
2018			
Flush-to-scrape	7	$4,417,467	$1,490,404
Solid separation	28	$14,042,182	$1,212,442
Compost bedded Pack barn	3	$2,127,529	$19,575
Total	38	$20,587,178	$2,722,421
2019			
Flush-to-scrape	7	$4,044,413	$640,488
Solid separation	30	$18,027,333	$1,220,180
Compost bedded pack barn	13	$9,381,188	$2,298,075
Total	50	$31,452,934	$4,158,743

Source: USDA, Economic Research Service using data from California Department of Food and Agriculture, 2021b.

Anaerobic digesters, though technically feasible for many U.S. farms, are often limited in their application to larger scale operations (500 cows or more) due to relatively high capital cost per animal. Even with subsidized support offsetting initial capital investments, small to mid-sized dairy farms lack the economies of scale operationally necessary to generate a positive return of investment and face higher uncertainty associated with an economic value of benefits, system reliability, rates of return, and risk of lost capital relative to large farming operations (Wang et al., 2021).

Community Digesters

Manure anaerobic digesters have substantial economies of scale, so in the United States, the technology has primarily been developed for, and adopted by, larger operations (CAFOs with greater than 1,000 animal units). The technologies favor large farms in terms of financial returns and renewable energy outputs. Large farms earn a reported 12.54 percent return on equity and 13.5 percent return on assets on their anaerobic digestion systems. Smaller farms earn 0.73 percent and 1.07 percent, respectively. After considering depreciation rates, net earnings for small and mid-sized farming operations are insufficient to pay back the investment and effort. In part, these outcomes are attributed to the high investment and maintenance costs associated with anaerobic digester projects, which are not scaled with herd size. Systems built on large farms cost less than half on a per cow basis than systems on small to medium-sized farms but earn nearly twice the revenue (Wang et al., 2017). Other factors also limit interest among smaller operations—such as lack of training and expertise, labor, and maintenance issues.

Community digesters represent a potential solution for small and medium-sized farming operations to overcome some of the economic obstacles associated with digesting waste. They locate centrally and accept manure and other farm and industrial wastes from multiple farms and off-farm sources (Swindal et al., 2010). Sharara et al (2020) showed community models to be more robust to uncertainty in prices and revenue streams by distributing investment costs across multiple operations and providing smaller operations a means to achieve economies of scale. Community digesters also provide regions in which they are located an opportunity to better meet waste-disposal needs, prevent nutrient pollution in surrounding waterways, reduce odor, and limit organic wastes going into landfills (Wang et al., 2021). This model may also provide flexibility in areas with winter manure storage issues. Not only the technical management but also transaction costs associated with utilities negotiation would be spread over more farms. In some cases, a minimal scale is required to connect to the grid, so working collectively can help meet the minimum.

Community anaerobic digesters are limited in their application to areas with several small to mid-sized dairy farms relatively close to one another. Although community anaerobic digesters or farmer-owned cooperatives offer potential economies of scale, economic returns can be easily offset by manure transportation and handling costs, which can pose a significant challenge (Thompson et al., 2013). For biosecurity concerns, it is important to ensure proper manure and digestate handling to not spread disease. Hauling manure and other feedstocks from multiple locations to a central facility and then moving digester effluent back to crop fields is energy intensive. Because manure has a relatively low specific biogas yield, it has been estimated that the maximum distance that dairy manure can travel is 13 miles before it requires more energy to move than can be recovered from the system (Pöschl et al., 2010).

Community anaerobic digester adoption and success has been limited in the United States. As reported in the AgSTAR database, farm-scale anaerobic digesters represented roughly 89 percent of all facilities in the United States since 1994. Community anaerobic digesters represented less than 9 percent, and research facilities represented 2.4 percent (U.S. Environmental Protection Agency, 2021d). Wang et al. (2021) observed community anaerobic digesters have a higher rate of shutdown, at roughly 31 percent, compared to farm-scale digesters at 24 percent. Limited research highlights the factors affecting anaerobic digester and community anaerobic digester sustainability in the United States. However, a 2021 case study in Vermont suggests that the lack of consistent quality and cleanliness of off-farm feedstocks (such as food waste; poor revenue performance; and significantly higher than expected operational, maintenance, and repair costs) may contribute to the abbreviated longevity of community anaerobic digesters, relative to other project types (Q. Wang et al., 2021). A survey of New York dairy farmers assessed farmer interest in community anaerobic digesters. The researchers found that more than half expressed some interest in community digesters, and larger farms were more interested (Swindal et al., 2010). Interest was predicted by perceived electricity benefits, neighboring residences, and considering water pollution a major issue. It was negatively associated with viewing the technology as complex. While energy prices and policies may differ in Europe, a study in Switzerland (Burg et al., 2021) also found that revenue from energy production was a main driver for biogas interest. Interest was lower for a large number of co-owners than for a partnership; most farmers preferred to own the digester themselves, all else equal. Similarly, a study in Denmark found that both the subsidy amount and the characteristics of the business model affect the willingness to participate in a partnership-based biogas investment (Zemo and Termansen, 2018). Interest in the biogas investment was increased by a smaller number of partners, a shorter distance from the farm, the ability to exit the contract, and the availability of consulting assistance. Larger farmers and farmers involved in off-farm economic activities had greater interest.

Policies that enable participation in subsidy programs by co-op producer-members could increase community anaerobic digester adoption. Many dairy farmers are already involved with cooperatives, which may increase the feasibility of this option for that sector. Although this section discusses community anaerobic digesters, cooperatives have also formed to achieve economies of scale with high-rate composters, such as one located in central Missouri.

Manure Thermochemical Conversion

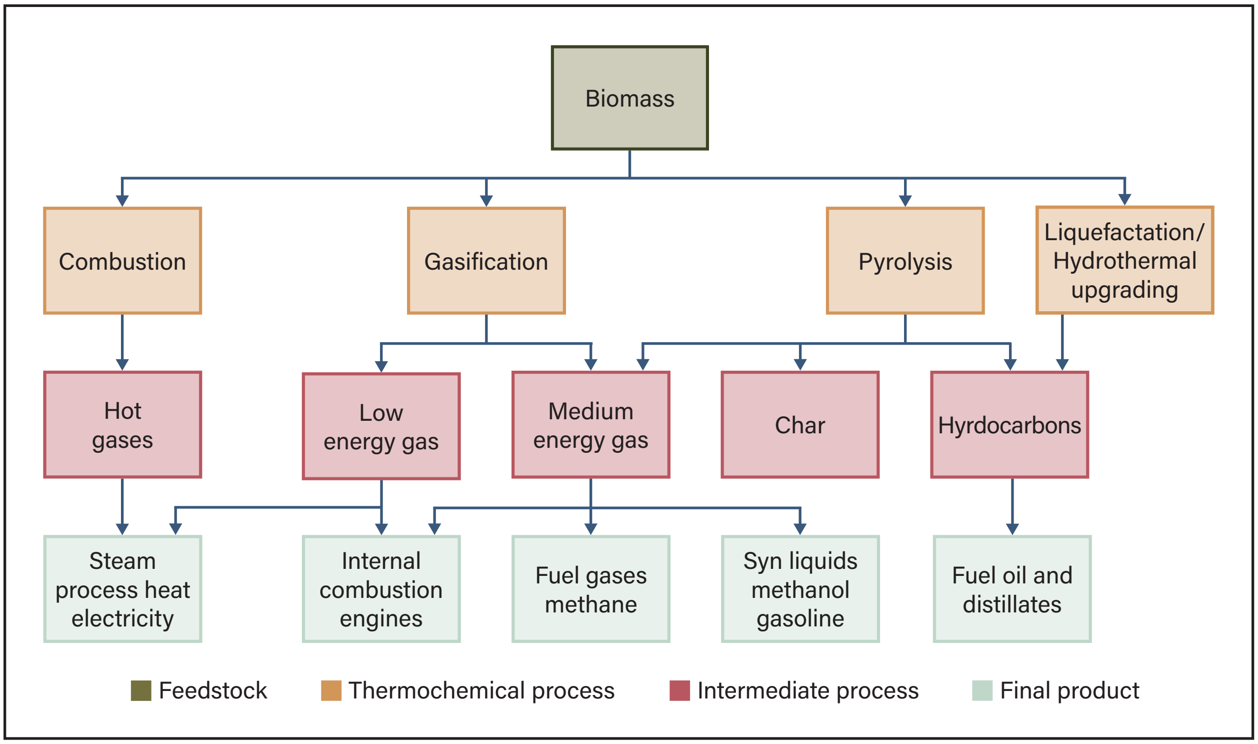
Anaerobic digestion's main products are methane-rich biogas and digestate, but alternative thermal treatments—or thermochemical processes such as gasification and combustion also yield fuel gases but at a much faster rate (Potts and Martin, 2009). Thermochemical processes provide different ways to trigger chemical changes to manure and other organic material. These chemical changes stem from reactivity with heat in a controlled environment. Thermochemical conversion yields synthesis gas and hydrocarbon fuels. The unreacted residual that remains after conversion is a combination of minerals referred to often as char or biochar (K. Cantrell et al., 2007).

Thermochemical conversion has several advantages compared with other biological manure treatments, including more compact operations, faster conversion, destruction of pathogens and most pharmaceuticals, no fugitive gas emissions, and potentially more efficient nutrient recovery (K. Cantrell et al., 2007). It also has its challenges. Toxic and hazardous materials (such as polycyclic aromatic hydrocarbons) can be present in the biochar, which is created when the thermochemical process is not complete. These byproducts can exist in the environment for long periods of time, with the long-term exposure effects on humans unknown (Hanson, 2016). Air quality concerns have been raised relating to the combustion of poultry litter for electricity production. The most cited concerns are air emission of arsenic, dioxins, furans, hydrochloric acid, sulfur oxide (SOx), nitrogen oxides (NOx), and hydrogen sulfide (Q. Ma et al., 2019). Furthermore, energy balances are negative, meaning it will use more energy than it will produce, particularly for wet manures that require energy-intensive drying and have relatively low energy density. These technologies are currently not likely to be viable on individual animal farms.

Pyrolysis, gasification, and direct liquefaction are the three main thermochemical conversion processes that can be incorporated into current manure management practices and have the potential to convert feedstock into value-added products (K. Cantrell et al., 2007). All three processes (depending on factors such as temperature and heating rate) yield a combination of volatile gases, bio-oil, and solids. These products' end uses fit into three categories: heat and power generation, transportation fuels, and chemical feedstocks

(McKendry, 2002). Energy produced from thermochemical conversion must first go through a cleaning process to remove tars, metals, water, and other byproducts that can corrode engines. Cleaning reduces the overall potential to recover energy. However, thermochemical conversion products can also act as "chemical intermediates" to create more energy-dense forms along a value chain (McKendry, 2002). Figure 15 illustrates major thermochemical conversion processes and final products of biomass, including manure.

Figure 15
Processes, energy carriers, and final products of thermochemical conversion of biomass



Source: Bioresource Technology, "Energy Production from Biomass (part 2): Conversion Technologies," Reviews issue, 83(1):47–54.

Combustion is the most common thermochemical conversion process. It can use manure as a fuel for generating heat or electricity. At one point, using manure as a combustion fuel was a viable option due to manure being a renewable fuel source. Previous reports listed several combustion plants as operational or coming online in the near future (MacDonald et al., 2009). Follow-up contact with those facilities revealed that all have shut down—some at considerable expense to the utility operating a given plant (details provided below). Poultry manure was the most common fuel manure, and beef cow manure ranked second. Transportation costs and poor burning qualities—due to relatively high moisture content compared with coal or wood—made manure an expensive fuel source at a cost of $0.06 per kilowatt hour to $0.08 per kilowatt hour. Typically, biomass with a moisture content below 50 percent—unless pre-dried—is considered feasible for combustion (McKendry, 2002). Subsidies greatly reduced the cost to produce electricity from wind and solar—down to $0.02 per kilowatt hour to $0.04 per kilowatt hour—disadvantaging fledging companies positioned to generate energy from manure combustion (Preston, 2021).

Gasification is another thermochemical process that converts biomass into more concentrated forms of potential energy in a multistep process. Dry gasification essentially uses air or steam to convert dry or wet feedstock into gases, such as carbon dioxide and hydrogen. It leaves behind a char byproduct (K. Cantrell et al., 2007). Biomass entering the system must be as dry as possible to maximize overall efficiency of the process, which includes pyrolysis (i.e., heating without air to make charcoal, or biochar, and "tar" gasses) and reduction (i.e., converting cracked tar gasses to hydrogen gas). The various steps in gasification require increasing amounts of heat. Pyrolysis takes place within the range of 350 °Celsius to 700 °C (K. B. Cantrell et al., 2012), while the reduction step requires temperatures up to 900 °C. (ALL Power Labs, n.d.). Gasification's final product is a low-energy fuel that can be burned directly or used in gas engines. If it is cleaned significantly, then the fuel can be turned into synthetic gas (i.e., syngas) which is commonly used in methanol, ethanol, fertilizer, and electricity production (McKendry, 2002). Smaller-scale biomass gasification plants differ from those found in large-scale industrial operations because they use air instead of oxygen in the gasification process. Gasifiers that use oxygen require an air separation unit that is typically cost-prohibitive for conversion using agriculture feedstocks (The Global Syngas Technologies Council, 2021).

Another thermochemical conversion process, pyrolysis—converts biomass into solid (charcoal), gaseous (fuel), and liquid (bio-oil) forms. It involves heating biomass up to 500 °C in the absence of oxygen, converting the organic portions of feedstocks into volatile gases and condensable tars and forming pyrolytic oil or bio-oil. The amount of charcoal, gas, and bio-oil is affected by temperature, rate, and time of the process. Slow pyrolytic processes use relatively lower temperatures (400 °C) and longer residence times to encourage char or solid production (K. Cantrell et al., 2007). Biochar produced from animal manure has the potential to be agronomically applied. It may improve soil quality by adding nutrients, reducing pathogens, and increasing organic content. Perhaps biochar production's biggest drawback is the high energy it consumes. Energy consumption is particularly significant if using wet manure. Dewatering feedstocks before pyrolysis helps to reduce energy consumption (Atienza-Martinez et al., 2020).

Comparatively, fast or flash pyrolysis has shorter residence times and burns at temperatures reaching 500 °C. It converts organics to liquid or bio-oil forms (K. Cantrell et al., 2007). This process has a reported efficiency of up to 80 percent. The bio-oil may be applied to engines or turbines or used as refinery feedstocks (McKendry, 2002). However, the oxygen-rich bio-oil is unstable and acidic. Adding catalysts can remedy this problem (Perry, 2014). The addition adds costs and complicates the process but results in a bio-oil more applicable to existing infrastructure.

Thermochemical Conversion Process: Challenges and Potential Barriers

The condition and make up of animal manure can be highly diverse in terms of moisture content, particle size, and composition. For dry gasification systems, uniformity of particulates is highly important to temperature propagation rates; therefore, some type of pelletization grinding, or blending, is necessary for manure feedstocks prior to use in thermochemical conversion. Additionally, feedstocks must be free of contaminants that can cause the thermochemical system to clog or render the operation ineffective by reducing peak temperatures. Ash found in manure contains alkaline salts and other metals. Although the ash is removed frequently throughout the conversion process, melted salts can combine with silica in dry gasification processes to form a sticky and highly mobile substance that blocks air flows and coats catalytic sites. This material would reduce temperatures in the process and affect gas quality (Cantrell et al., 2007).

Other challenges manure thermochemical processes face are the elevated levels of nitrogen oxides, sulfur oxides, dioxins, particulate pollution, and other toxins potentially released when biomass is incinerated. Stingone and Wing (2011) summarize the significant risk to public health and the environment posed by poultry litter when used as a feedstock.

Increased costs to meet emission limitations, high capital costs of equipment (Preston, 2021), moisture limitations of feedstocks, current process inefficiencies, and economies of scale needed for on-farm applications of commercial methanol synthesis technologies act as significant barriers to adoption (McKendry, 2002). Pretreatment and process technology improvements, in conjunction with alternative energy incentives, continue to fuel the promise of thermochemical conversion technologies for on-farm application in the future.

Combustion Plant Updates

The 2009 report on manure in the United States listed several combustion plants that had come online or planned to go online (MacDonald et al., 2009). These included GreenHunter Energy (Imperial, California), Fibrominn/Fibrowatt (Benson, Minnesota), and Panda Ethanol (Hereford, Texas). The current operating status of these plants is as follows:

- **GreenHunter** filed for bankruptcy in 2016. It never operated the powerplant. It sold the asset months before bankruptcy to Mesquite Lake Water and Power. The power plant still does not function because costs of producing electricity from solar and wind are much cheaper due to 30 percent Federal subsidization and other factors. The Mesquite Lake owners say they need to sell electricity for $0.07 per kilowatt hour, but wind and solar can sell at $0.03 per kilowatt hour (Williams, 2020).

- **Fibrominn/Fibrowatt** had been working to develop biomass co-generation plants in several States including Minnesota, Michigan, Maryland, Pennsylvania, Arkansas, Mississippi, and Georgia. It is not clear how many of these have matured into active installations. Their first plant began operation in 2007 but ceased operation in 2017 and was demolished in 2019. Electric generation costs at the plant were too high to compete with other sources of energy ("Fibrominn," 2020). No evidence of other Fibrominn plants in the United States can be found.

- **Panda Ethanol,** a subsidiary of Panda Energy International, declared bankruptcy and sold the Hereford plant assets during the late stages of construction in 2009. Three other plants in the planning stages in 2009 were to be located in Kansas, Texas, and Colorado. It does not appear any were built (B. Sims, 2009). Panda's business model involved a dual-energy approach whereby manure would be burned to fire boilers that (1) produce steam for turbines and (2) allow for spent steam to pre-process materials for ethanol fermentation. Panda Energy International shut down its operations in 2018 because, according to Panda chairman Janice Carter, "Independent power companies can no longer compete in today's power market against government-subsidized renewables, such as wind" ("Panda Energy International," 2021).

Biomass combustion as a renewable energy source does not appear to be competitive with more heavily subsidized renewables (i.e., wind and solar) when those other sources can be reasonably implemented or a significant distance exists between the biomass combustion plant and fuel source. Some areas in the United States have better conditions to support biomass combustion. Lumberton, North Carolina, is an example. North Carolina Renewable Energy, a Georgia Renewable Energy subsidiary, upgraded an old coal-fired powerplant with a new boiler and converted it into a biomass combustion plant with Duke Energy support in the form of renewable energy credits. An interview with an industrial control engineer revealed the following details about the plant, its operation, and biomass combustion (Utley, 2021):

- Startup and controls were difficult at first. Biomass comes from several farms, and the various inconsistencies in terms of composition and heat potential resulted in abnormally frequent control changes. An automated system was developed to help the operators.

- Poultry litter creates a lot of ash and residue when burned and causes a lot of corrosion. It requires a special boiler and approximately weekly shutdowns for cleaning. Shutdowns are noisy and can result in complaints from the public if not properly managed. System interruption reduces productivity, and the cleanings represent added maintenance cost.

- The plant is offline until 2022 because of a disruption to, or negotiation over, the renewable energy credit contract—presumably with Duke.

- Biomass combustion can work well if it can co-generate multiple fuels and pair with local industry needs to purchase post-turbine steam for heat or internal processes. Example industries include papermills, chemical plants, and ethanol and petroleum refineries.

Maryland and Pennsylvania have a couple of notable projects that appear successful, in part, because of efforts to reduce the Chesapeake Bay's nutrient load by way of credit trading and grant support. Hillendale Farms in Gettysburg, Pennsylvania, supplies poultry litter from 5 million layers to a 2.5 megawatt gasification plant owned by EnergyWorks (EnergyWorks, 2013). The company projected a revenue plan with a 40-40-20 split to 1) eco-services generating nutrient trading credits, 2) fertilizer and animal feed sales from fly ash, and 3) electricity sales, respectively (P. Thompson, 2021). Challenges for Energyworks include a nutrient trading market that has not been sustainably established and fertilizer and feed markets have not matured to a level that provides desirable income. The facility is not currently operational but might be with State subsidies under a "pay-for-performance" agreement. The technology is applicable to various manure stocks, but input consistency is important to produce reliable fertilizer and feed outputs and hit emissions targets.

In Maryland, the State's energy and natural resources departments contract with technology vendors who install manure treatment equipment on partner farms. University of Maryland Extension provides technical support and third-party performance verification. The program's approach is evolving to focus on regional technology application, rather than farm-by-farm application. This shift is due to the lack of a sustainable business model for vendors who cannot afford to provide long-term technical services to a single farm without other monetary compensation. The program's newest pilot unit is with International BioRefineries LLC; it should become operational in spring 2021 (Mulkey, 2021). International BioRefineries LLC received a $1.9 million grant from the Maryland Department of Agriculture in 2020 to install a fast pyrolysis plant in Finksburg, Maryland. The plant will process 1,000 tons of chicken manure per year to reduce volume by 50 percent and produce bio-oil, biochar, and syngas (Maryland Department of Agriculture, 2020).

Fiber Products

Anaerobic digestion systems can convert manure into heat, power, fuel, fertilizers, fiber, wood composites, and biochar. The marketing of coproducts, such as digestate solids—undigested biomass from digester effluent—can bolster the revenue potential of digesters and encourage their adoption (Kirk and Gould, 2019).

Dairy manure contains fibrous solids, some of which survive the cow's digestion process. This fiber comprises roughly 40 percent to 50 percent of total solids in dairy manure, and it remains largely intact after processing in typical mesophilic anaerobic digestion systems. Manure fiber can be an important input for both processing and developing value-added products (Pelaez-Samaniego et al., 2017). After anaerobic digester treatment, this fiber can be extracted from digestate using solid-liquid separation technologies, such as screw press separators and slope screens. The fiber includes microbial biomass, animal hair, undigested organic materials, and nutrients (Kirk and Gould, 2019).

Existing anaerobic digesters frequently earn income from extracted manure solids. Simple mechanical screens, with scale variable capital ($45–80 per cow) and operating costs ($8–16 per cow per year), can effectively separate the fiber from the manure and/or wastewater (Pelaez-Samaniego et al., 2017). The anaerobic digestion process reduces pathogens and stabilizes the organic carbon found in the fiber (Yorgey et al., 2011). Below are some value-added products made from this fiber.

Bedding

To process digestate fiber into bedding requires relatively dry environments to keep pathogen concentrations low. Several companies producing high-performance slurry separation machinery, processing technologies, and drying technologies have entered the market (Leach et al., 2015). Approximately 50 percent of the fiber produced by a dairy farm fulfills its internal needs. The farm can direct the remainder to other value-added products or sell it as bedding to other farms that don't have a digester (Pelaez-Samaniego et al., 2017). It has been estimated that using digestate solids as bedding produces a cost offset in the range of $23 to $30 per 1,000 gallons or $21 to $27 per wet ton (Yorgey et al., 2011).

Growth Substrate, Growing Media Component, and Containerized Plants

Growing high value crops in greenhouses and nurseries is a specialized segment of the horticulture industry. Roughly 80 percent of plants in greenhouses and nurseries grow in containers (Pelaez-Samaniego et al., 2017). The selection of the growing media, or substrate, in a container is an important consideration for plant growth (Lamont, 2015). Growing media used in greenhouse container production is composed of roughly 80 percent organic materials. Peat and bark have been primary components (Pelaez-Samaniego et al., 2017) since the 1970s. However, growing environmental concerns, scarcity issues, and price pressures have prompted the industry to seek more economical and sustainable alternatives (Pelaez-Samaniego et al., 2017). A growing body of research highlights the potential for anaerobically digested manure fibers to work as high-quality growth substrate for soilless horticultural producers. The digestate has similarities to peat such as high fiber content, long fiber length and good air porosity, spongy texture, high nutrient content for root development, and water retention capacity (Ma et al., 2016).

Peat moss use in horticultural applications totals roughly 6.8 million tons per year and replacements have significant market potential (Carlile et al., 2015). It has been estimated that anaerobic digestion operations using dairy manure could achieve roughly \$10.50–\$17 per cubic yard for bulk quantities of digester fiber marketed as peat replacement with wholesalers covering transportation costs (Ma et al., 2016). However, challenges remain to meet growers' needs for substrates that are standardized, reliable, free of odor and pathogens, economical, and available (Pelaez-Samaniego et al., 2017). Blending and additional treatment—such as composting to further the breakdown of fibers, drying, and heating—are currently being explored in an effort better align the fiber's physical properties to the industry's needs (Ma et al., 2016).

Biodegradable Containers

Biopots, or biodegradable plant pots, are often made of byproducts or wastes. They act as a green alternative to plastic containers for consumer, greenhouse, nursery, and landscaping segments interested in floriculture (Zhang et al., 2019). The biodegradable plant pot may offer an opportunity for farmers to bolster on-farm revenue and reduce the environmental impact of multiple waste streams: plastics and manure.

Biopots are typically classified into two categories: plantable and compostable. Compostable biopots—generally made from bioplastics based on rice hulls, starches, wood pulp, and polyactic acid—give containers more structural strength. They prevent plant roots from growing through their walls and can last a long time. Although these pots cannot be placed directly in soil with transplants or seedlings, they can be discarded in compost or landfill facilities where they will eventually degrade. In contrast, plantable biopots can be buried in the soil directly with the plant. They reduce planting effort and labor, disposal costs, and environmental contamination (Al-Ahmed and Inamuddin, 2020). Typically made from organic materials such as composted manure, wood fiber, coconut husk, peat, or recycled paper—plantable pots may reduce or eliminate root disruption and transplant shock in seedlings and young plants, as well as eliminate waste (Nambuthiri et al., 2015).

In 2013, 4 billion plant containers are produced annually in the United States, of which the petroleum-based plastic containers accounted for approximately 1.6 billion pounds of plastic (Harris et al., 2020). The majority of these plastics end up in landfills or burned in uncontrolled environments (Al-Ahmed and Inamuddin, 2020). Agricultural plastics are a particular challenge to recycle due to contamination from ultraviolet light degradation, pesticide residues, or growing media contaminants (Hall et al., 2010).

A large body of research has emerged in the past several decades to assess biopot efficacy, quality, and marketability. In field trials, Sun et al. (2015) examined how seven different plantable containers, made of various agricultural and industrial wastes, affected plant quality and development as well as container decomposition. The impact of containers on plant quality and growth varied with climate, growing season, and plant variety, and containers made from manure had the highest decomposition rate (Al-Ahmed and Inamuddin, 2020; Sun et al., 2015). This is a positive attribute since rapid decomposition is necessary to avoid root circling, water and nutrient restrictions, and the accumulation of pots in fields (Zhang et al., 2019).

Biopots can be as much as 10 percent to 40 percent more expensive than traditional plastic containers. Therefore, growers must offer a more desirable product or reduce their operational costs to make biopots economically feasible (Nambuthiri et al., 2015). A 2010 study reported that consumer demand for biodegradable pots had increased, relative to plastic ones (Hall et al., 2010). Another study found that individuals were willing to pay a price premium for biodegradable pots, depending on the type of plants (Yue et al., 2010). Consumers reported they were willing to pay as much as $0.50 to $1 more for plants grown in biodegradable pots, compared to those grown in plastic.

From a commercialization perspective, a 300-cow dairy located in East Cannan, Connecticut, developed a patented process of converting digestate fiber into biodegradable plant pots in an effort to add revenue streams and bolster the profitability of its on-farm anaerobic digester (Ma et al., 2016). Using molded digestate from a plug flow digester, the owners produce a weed- and seed-free pot that dissolves in the ground, after which it provides a nutrient-rich foundation for young seedlings (U.S. Environmental Protection Agency, 2021d). The project took 8 years to develop and was supported by a $72,000 Federal grant, secured by Connecticut's Agricultural Businesses Cluster. The project released its first marketable product made by hand in 2007 (Hirshey, 2009). By April 2015, the operation had grown into a manufacturing, storage, and distribution success story (employing 30 people year-round and distributing the product across the United States) (Ma et al., 2016).

Summary

Table 8 summarizes the main technologies that were discussed in this section and it describes the production systems that align with the manure-related economic opportunities. It also articulates how several key themes—farm size, benefits, costs, and adoption barriers—apply when considering manure-related economic opportunities.

Table 8
Summary of economic opportunities

Technology	Relevant system	Economies of scale[a]	Benefits	Barriers
Manure application and composition modifications				
Subsurface application	Liquid and slurry manures (dairy and hogs).	Medium to large farms.	Increases nutrient retention and value. Reduces odors.	Requires more acres to distribute manure; requires specialty equipment and is more labor-intensive than surface application.
Nitrogen amendment	Liquid and slurry manures (dairy and hogs).	Small to large farms.	Balances nutrients to meet crop needs, reducing additional fieldwork to apply commercial fertilizers	May prevent manure from being eligible as an organic fertilizer.
Alum	Poultry litter.	Small to large farms.	Increases nitrogen and phosphorus fertilizer value. Improves animal health.	Cost of alum.
Acidification	Slurry manures (beef, dairy, and hogs).	Small to large farms.	Increases fertilizer value by preserving nitrogen. Improves animal health. Reduces greenhouse gas emissions.	Human health risk.

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Technology	Relevant system	Economies of scale[a]	Benefits	Barriers
Composting				
Windrow composting	Dry manure (beef cattle and poultry).	Small to large farms.	Produces valuable soil amendment products with steady market demand as organic fertilizer.	Space and cost; run-off control needed.
High-rate composting	Dry manure (beef cattle and poultry).	Moderate to large farms.	Smaller footprint, soil amendment products, and steady market demand, can be combined with windrow to balance cost/space.	Costs; specialty equipment and higher electrical usage.
Compost bedded pack barns	Primarily dairy.	Small to medium farms.	Animal comfort and health. Valuable soil amendment with steady market demand.	Carbon source cost; daily tilling required.
Vermicomposting	Dry manure (beef cattle, poultry, and scraped dairy).	Small to medium farms.	Manure is used to produce worms, co-product with higher value.	Cost; space, facilities, managerial complexity; lack of worm market; requires nutrient adjustment.
Larvae-based composting	Dry manure (beef cattle, poultry, and scraped dairy).	Small to medium farms.	Manure is used to produce larvae, co-product with higher value.	Cost; space, facilities, managerial complexity; lack of larvae market or requires further, more complex, processing; requires nutrient adjustment.
Technologies that separate solids from liquid				
Screens and sedimentation basins	High-moisture manure (dairy and hogs).	Small to large farms.	Separates coarse solid/grit; improves transport/handling/management and recycling potential.	Cost varies depending on sophistication of technology—passive or mechanical; represents a change to current operations.
Centrifuge	High-moisture manure (dairy and hogs).	Medium to large farms.	Separates solids; improves transport/handling/management; decreases nutrients in the liquid fraction.	High cost (time and money, energy); managerial complexity; polymer might be needed.
Filtration	High-moisture manure (dairy and hogs).	Medium to large farms.	Separates solids; improves transport/handling/management; reverse osmosis can remove nutrients and produce potable water.	High to very high cost and energy use; costs increase dramatically for higher quality filtrate, managerial complexity.
Dissolved air flotation	High-moisture manure (primarily dairy).	Medium to large farms.	Removes fine solids; improves transport/handling/management; potential byproduct market.	High cost; managerial complexity; labor intensive.

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Technology	Relevant system	Economies of scale[a]	Benefits	Barriers
Technologies that separate liquid from solids				
Presses	Dairy and hogs.	Small to large farms.	Removes water from solids; reduces transport cost; ease of handling, may be used directly for dairy bedding.	Cost.
Drying manure	Primarily poultry; some dairy and cattle.	Medium to large poultry farms; medium dairy and cattle farms.	Decreases manure weight; reduces odor and pest problems; potential organic fertilizer.	Costs are highly variable depending on manure moisture and climate; retrofits expensive; high energy costs; loss of nitrogen; certification needed for organic product.
Other types of fertilizer products				
Pelletizing	Dry manure (beef cattle and poultry).	Large farms.	Can be organic; compact and lower transport costs so can address nutrient surplus production areas; can adjust nutrient content for specialty markets.	High cost to very high cost; potential niche markets rather than commodity market; certification needed for organic product; may require significant pretreatment.
Vermifiltration	High-moisture manure (dairy and hogs).	Scalable but better for small to medium-sized farms.	High-value fertilizer; removes nutrients from liquid.	Cost; managerial complexity; lack of worm market; requires moderate pretreatment.
Struvite	High-moisture manure (dairy and hogs).	Large farms.	High-value phosphorus-based fertilizer; improve farm nutrient management options.	Very high cost; managerial complexity; biosecurity issues with shared equipment; requires significant pretreatment.
Energy production				
Anaerobic digesters	Potentially all, not common for poultry.	Large farms with potential for small to medium depending on manure management and distance, if co-op or shared equipment.	Biogas generation; consistent digestate; solids, odor and pathogen reduction.	High cost to very high cost; managerial complexity; renewable energy contract constraints.

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Technology	Relevant system	Economies of scale[a]	Benefits	Barriers
Energy production				
Algae	High-moisture manure (primarily dairy).	Medium to large farms.	Produces a variety of value-added products: biodiesel, ethanol, fertilizer, and animal feedstuff.	High cost to very high cost; lack of market for algae and nutrient trading; infrastructure complexity; best in warmer and sunny regions; expensive processing equipment needed to access value-added products.
Thermochemical conversion	Low-moisture manure (beef and poultry).	Large farms.	Different forms of renewable energy and other marketable products.	Very high cost; capital and operational costs; managerial complexity; renewable energy contract constraints.

[a]A large farm has more than 1,000 animal units. A medium farm has 300 to 999 animal units. A small farm has fewer than 300 animal units. One animal unit is equivalent to 1,000 pounds live weight of animal. Because animal weights differ by type of production, the U.S. Environmental Protection Agency specifies that 1,000 animal units would equal 1,000 head of beef cattle, 700 dairy cows, 2,500 pigs, or 30,000 broilers (EPA, 1995).

Source: USDA, Economic Research Service using data from U.S. Environmental Protection Agency, 1995. Guide Manual on NPDES Regulations for Concentrated Animal Feeding Operations, EPA 833-B-95-001.

Government Programs and Policies

Government programs and policies can influence farmers' manure management decisions (directly and indirectly) with consequences for farm profits, the environment, and public health. In this section, we discuss how government programs or policies could be used to promote the adoption of value-adding manure technologies.

Animal producers are subject to government policies at the Federal, State, and local levels. Often Federal agencies delegate responsibility to States and local offices. The EPA may delegate authority to states to develop their own programs that comply with Federal regulations, such as point-nonpoint source water quality trading allowed under the Federal Clean Water Act. The USDA NRCS uses State technical committees to help set priorities for program emphasis. States also have their own programs that the Federal Government may consider as templates for future action.

The policy options below have been demonstrated to be technically feasible, are applicable to more than a few livestock operations pursuing niche markets, and have the potential to both improve environmental performance as well as farmer incomes.

Financial Incentives

Financial incentives make new technologies or practices less expensive to farmers and thus help to overcome the cost barrier. Program payments can facilitate adoption of technologies or practices that may be profitable in the long run but have high up-front costs. The USDA Environmental Quality Incentives Program (EQIP) program is a voluntary conservation program that offers farmers and ranchers financial cost-share and technical assistance to implement conservation practices on working agricultural land. EQIP could increase payments for the purchase and implementation of targeted technologies—e.g., manure separation, composting facilities, and anaerobic digesters—which would have the effect of directly lowering the cost of adoption of the technology for farmers. While several technologies discussed in the report are currently eligible for EQIP funding, in some cases, demand for EQIP payments exceeds current funding levels. Better targeting of existing EQIP funding or an increase in future funding could therefore result in greater adoption of these technologies and practices.

Loans and grants assist farmers in accessing new technologies and starting new businesses. USDA programs could increase the focus of loans and grants on manure related technologies and businesses. As mentioned above, USDA Rural Development's REAP program provides guaranteed loan financing and grant funding for anaerobic digesters (U.S. Department of Agriculture, Rural Development, 2020). The Farm Services Agency provides direct and guaranteed loans that may be used to purchase machinery and equipment or assist specialty operations (U.S. Department of Agriculture, Farm Service Agency, 2019).

In addition to the Federal Government, States also provide funding for agricultural conservation programs. Several examples have already been discussed in relation to specific technologies. As with Federal programs, State agricultural conservation programs typically fund conservation projects through a cost share structure in which farmers pay a percentage of the project costs and receive the rest from the public program. State agricultural programs often serve as an additional source of funding that supplements Federal funds. Some State programs may serve as innovative pilot programs for Federal programs (Feldman et al., 2019).

An example of an innovative State program is the Maryland Manure Transport Program. This program provides funding for farmers accepting manure, provided the receiving fields have an appropriate soil phosphorus fertility index (Maryland Department of Agriculture, n.d.). Similarly designed programs could target multistate manuresheds and critical source areas so that farmers have an increased incentive to appropriately use manure as a fertilizer.

Tax credits are another tool which provides a financial incentive for growers to adopt new technologies or practices. For example, EPA has energy efficiency tax credits for both households and home builders (U.S. Environmental Protection Agency, 2021a). A number of States have used transferable conservation tax credits to help farmers finance conservation practices (Feldmann et al., 2019). With a transferable conservation tax credit, a State provides tax credits to landowners at a certain percentage of the cost of the best management practices being implemented. The tax credit can be used to directly reduce the landowners' tax liability, or it can be sold to another taxpayer in exchange for cash.

Regulation

As discussed in the second section, the U.S. Environmental Protection Agency regulates discharge and run-off from some agricultural facilities under the Clean Water Act. Regulations govern the construction and management of manure storage facilities, the land application of manure-supplied nutrients, and the methods and timing of manure application. The value of manure depends, to some extent, on the stringency of environmental regulations imposed by EPA and other agencies. In addition, regulation can lead to technological innovation with indirect positive effects on productivity growth (Hille and Möbius, 2019). Many smaller-scale operations currently have little financial incentive to adopt costly manure technologies and practices that could improve environmental outcomes because these small operations are not regulated. Since there is little incentive to adopt new technologies, there is also little incentive for firms to create technologies suitable for smaller operations (McCann et al., 2005). A phased-in approach to regulation of smaller-scale operations could lead to technical innovation and thus increased value of manure nutrients and improved environmental quality. Technical innovation could result in new technologies that are appropriate for smaller operations, or lower costs for the manure management technologies discussed above. However, a phased-in regulatory approach may need to be accompanied by economic incentives to enable firms to transition to the new technologies. As discussed above, not all technologies are feasible for all sizes of farms, and some farms might be unable to meet new regulatory requirements and remain profitable.

Community (Multi-Farm) Systems

By collaborating, small and medium farms may share expenses, risk, and expertise; take advantage of economies of scale; and more readily adopt certain technologies, as explained in the previous section on technologies. Central digester/composting refers to a system where small farms can deposit manure or have it picked up for further processing. Small farms benefit by having access to off-farm processing that would otherwise be too expensive for their size. They receive a share of the income generated by the processing and any remaining by-product for their use. Some community systems pay farmers for manure. States have used tax credits to foster community systems and the Federal Government could examine these programs to create a template for how to facilitate these systems at the Federal level.

Existing law provides favorable Federal tax treatment for farmer cooperatives. Programs to support farmer collaboration may incentivize co-op formation and participation in value-added manure economic opportunities. As an example, changing rules to allow multi-farmer organizations to apply for Federal financial incentive programs, such as EQIP, could help promote these organizations and facilitate the adoption of manure management practices and technologies.

Nutrient Trading Programs

Federal policies and regulations influence incentives for farmers to participate in State nutrient trading programs that were described above. To date, the number of point-nonpoint nutrient trades have been limited. The EPA could examine current State programs and related research and help facilitate the design of nutrient trading programs that increase incentives for livestock producers to participate.

Factors that have been identified by researchers as impediments to successful participation in trading programs include: the farmer's cash flow and upfront costs of lowering discharges, the uncertainty that adopting best management practices will produce credits, transaction and trading costs, trading ratios, producers' attitudes about regulation (e.g., fear or distrust), producer flexibility, and interactions with other conservation programs or subsidies (Sneeringer, 2016; Ribaudo and Gottlieb, 2011; Motallebi et al., 2017; Fleming et al., 2020a). Ribaudo and McCann (2012) examined the transaction costs of nutrient trading in Pennsylvania and determined trading costs were not substantial, and other design characteristics such as baseline requirements (having a buffer around surface water or achieving a 20 percent reduction of the farm's overall nutrient balance) were more likely to inhibit trades.

Other research suggests that the design of water quality trading programs can be improved by focusing research on credit generation from particular practices that are easy to verify (Ribaudo and Gottlieb, 2011), identifying potential impediments to participating in trading programs (Motallebi et al., 2017), and reducing the opportunity for nonpoint sources to choose among multiple conservation programs in a way that increases the societal cost of nutrient abatement (Fleming et al., 2020). Based on farmer interviews, a study by the American Farmland Trust concluded that farmers also were concerned with the quantity and complexity of contracts, access to technical assistance, and the use of trusted intermediaries (Sorensen, 2011).

Renewable Energy Policy

The Federal Government could modify the design of renewable fuel policies to further encourage participation by livestock producers. Manure and other cellulosic material can be used to create renewable natural gas that can generate tradable RINs with market value if injected into a utility pipeline. The existing renewable fuel programs were described above, as was California's Low Carbon Fuel Standard, which has stimulated investment in anaerobic digesters.

Several hurdles stand in the way of manure producers benefitting from the Renewable Fuel Standard. Obtaining sufficient funding for a renewable energy project can take years of fundraising. Obtaining sufficient manure feedstock can require project developers to meet requirements of animal farmers and develop creative business arrangements with farmers. Finding sufficient manure feedstock near a pipeline access can also be challenging (BioCycle, 2019).

Renewable electricity is another potential revenue source from manure. Policies that relate to selling renewable electricity to the grid vary from State to State, which may disadvantage producers in some States. More research is needed on adoption of renewable electricity from manure and policy impacts on adoption (e.g., comparing performance-based incentives versus net metering).

Pricing Greenhouse Gas Emissions Reductions

Policies that pay farmers for greenhouse gas emissions reductions are increasing the value of manure. Projects that capture methane and inject it into RNG pipelines, with the capability of transporting it to California, are receiving substantial incentive payments. Farmers could be compensated for emissions reductions directly with government payments or through offset sales in carbon markets outside of California. Digester adoption can substantially reduce carbon emissions from confined animal operations (Key and Sneeringer, 2011b; 2012). Cap-and-trade systems could encourage the adoption of methane digesters if these systems allow producers to sell carbon offsets in a carbon market. Under such a system, livestock producers who reduce methane emissions via digester adoption could sell carbon offsets to other greenhouse gas emitters (such as electric utilities) that face emissions caps. California's greenhouse gas cap and trade program has facilitated the installation of methane digesters in that State since 2015 (California Department of Food and Agriculture, 2021b). As indicated earlier in the report, manure can increase organic matter in the soil and thus sequester carbon. Farmers could be compensated for this carbon sequestration.

The State of California and the Regional Greenhouse Gas Initiative[11] both allow the generation of GHG offsets by capturing methane released from manure (California Air Resources Board, 2020; The Regional Greenhouse Gas Initiative, 2021). Requirements for generating offsets differ between the two systems. These differences affect the demand and supply for GHG offsets by animal feeding operations. An Act that passed the Senate in 2021 would, if enacted, direct the USDA to try to "reduce barriers to entry for farmers, ranchers, and private forest landowners in certain [greenhouse gas] voluntary markets (117th Congress 2021)." Research into how these two regional approaches affect farmer participation could help the USDA achieve this objective.

[11] A cooperative effort of 11 northeastern States.

Applicator Certification

Increasingly, custom applicators handle manure application and often are able to do so more efficiently than individual farmers. The USDA could facilitate certification programs to improve and harmonize applicator training and allow applicators to earn premiums for their services. Insurance companies may encourage certification by reducing rates for farms using certified applicators. Support of custom applicators could also include programs that allow them to bundle manure with commercial fertilizers to provide a coordinated, balanced fertilizer program. Such programs would be more effective with the development of better manure testing technologies. Certified manure applicators could potentially participate in ecosystem markets or facilitate farmer participation.

Federally Funded Research and Development

Increased Federal support for university and USDA research could lower farmers' costs over time for manure-related technologies, such as anaerobic digesters and pelletizing. Research could also inform the development of policies and regulations pertaining to manure storage and use (Pannell et al., 2018). In general, returns to public research and development in agricultural production have been substantial, averaging 65 percent annual rates of return, according to a meta-analysis by Alston et al. (2000). Jaffe et al. (2005) noted that there are market failures associated with environmental pollution and also market failures associated with the innovation and diffusion of new technologies. These market failures imply that the private sector will underinvest in technologies to reduce pollution, which creates a strong rationale for public policies that promote the development and adoption of environmentally beneficial technologies. The USDA Conservation Innovation Grant program currently supports the development of technologies, including manure technologies, that advance conservation objectives (U.S. Department of Agriculture, Natural Resources Conservation Service, 2021). As indicated above, economies of scale are an important barrier, so modifying the program to incentivize research on technologies that are adapted for smaller farms may be beneficial.

A rigorous life cycle analysis related to livestock and poultry production could be part of research efforts to understand the elements of manure systems and how to improve them. For example, production systems that use less water facilitate value-added opportunities, and barns designed to separate solids or compost manure in sheds improve manure's economic value, as explained in the previous section. Related research could examine break-even transportation distances for manure as a function of production system, manure nutrient content, commercial fertilizer values, costs of application for manure and commercial fertilizers, crop receiving the manure, and other factors identified by Paudel and McIntosh (2005).

Research that takes a holistic systems approach can result in more efficient outcomes. Improved manure management should be integrated into decisions regarding facilities and livestock production practices, rather than being addressed after those other decisions have been made. For example, developing production systems that decrease manure's water content or modify its nutrient chemistry—rather than address these issues separately—will increase manure's value and facilitate some manure technology adoption. Such a holistic approach to animal production and manure management is facilitated when the research is interdisciplinary and incorporates animal nutrition, engineering, soil science, and economics. This research may in turn lead to new technologies or combinations of technologies. While most research on the environmental impacts of livestock and poultry operations relates to water quality, air quality impacts are also important and is a subject needing more research (Domingo et al., 2021). Private sector research could be facilitated by involving integrators in manure management. The current system, in which production decisions are made by integrators and manure management decisions by contractors, does not facilitate a holistic approach.

Research to develop scalable manure management technologies could support adoption on smaller farms. Smaller scale digester systems have been widely adopted in Europe, as reported in the previous section. However, industry sources in the United States indicate that most available digester technologies are not easily downsized. As a result, community and centralized facilities would be required for greater participation by smaller scale operations. Increased adoption of capital-intensive technologies on a wider scale would likely require research to reduce capital costs, operating costs, and technical complexity and would require educational programs to increase the knowledge and technical capabilities of farmers. Research funded by the EPA or USDA to understand why some operations were more successful than others in adopting and maintaining manure digesters could lead to improved understanding of what types of research should be prioritized.

Further research could improve our understanding of the barriers to greater manure use on specialized crop farms (Nunez and McCann, 2008). For example, research that examines the barriers to effectively combining manure and commercial fertilizer use for crop production may result in improved manure utilization. This information could inform extension efforts to promote the use of manure nutrients. The potential for manure brokerages to reduce transaction costs and facilitate manure market functioning is another area for future research.

Conclusion

There are 391 counties in the United States where more manure-derived phosphorus or nitrogen is produced than can be used by the crops grown within the county. In these counties with a surplus of manure nutrients, manure will have a relatively low value. At the same time, less than 19 million acres of land planted in 7 major field crops are applied with manure—less than 8 percent of the land used to produce these crops. Hence, there is substantial opportunity for increased use of manure to meet crop nutrient needs.

However, there are several challenges to expanding the use of manure as a crop fertilizer. In particular, transportation costs are high because manure has a low nutrient to mass ratio, manure can be costly to apply, and the ratio of manure nutrients may not match the needs of crops. The report reviewed several available and emerging technologies for addressing obstacles to increasing manure use as a fertilizer and also reviewed alternative uses.

Relatively simple solid-liquid separation technologies are precursors to several value-added opportunities for farms, even for operations producing and managing slurry manure. Separating liquids from manure facilitates transportation and yields liquid and solid components that can be further processed. Pelletization is another promising option for expanding the market for manure nutrients. Made from fiber, fine solids or manure from poultry, pellets are more easily transported. Their contents can be adjusted to specific nutrient ratios, and they can serve as slow-release fertilizers less susceptible to nutrient losses.

For some operations, composting manure can create a value-added product that is more easily transported and can be used in organic production of fruits, vegetables, and field crops. Increased adoption of high-rate composters would help producers meet the growing demand for compost used in organic production.

In terms of nonfertilizer uses for manure, possible ways to add value include anaerobic digestion, combustion (i.e., thermochemical conversion), and fiber recovery. Anaerobic digestion has recently increased in popularity with the onset of carbon credit trading and incentive programs. More covered lagoons have been constructed due to lower costs, and many of the newer digester projects are designed to produce compressed natural gas instead of electricity to allow for pipeline injection to take advantage of transportation credit trading programs.

Thermochemical conversion has had limited success, due to the high cost of manure combustion—primarily due to variability in heat value, moisture content, molecular or elemental content variability, and subsidies to other renewables (e.g., wind, solar) that make manure combustion less competitive. Some thermochemical conversions may have greater economic viability and benefits. These include pyrolysis for biochar generation and gasification for hydrogen gas production. Biochar can be used as an organic soil amendment and has demonstrated the ability to reduce pathogens in soils irrigated with liquid manure or lagoon supernatant. Hydrogen gas production may become more viable if the United States migrates to hydrogen fuel cells as a mobile energy source.

Digestion and thermochemical conversion technologies continue to improve, thanks to increased knowledge, as well as advancements in control systems and sensory technology. Other innovations in manure treatment processes—those in the development to early commercialization stages—have potential to increase renewable energy production. These include 1) larvae-based composting for ethanol fermentation or biodiesel production and 2) algae growth for biofuel or methane production.

The high fixed costs and resulting economies of scale for many of these technologies serve as a barrier to improving farm revenue opportunities for smaller-scale operations. Because many of these technologies have technical complexity, producers may require education to learn how to pursue these opportunities. Some companies are contracting with producers to build digesters at no cost to the farmer (NYSERDA, 2014). This symbiotic relationship provides the farmer with a means of manure treatment and additional income, without having to purchase and operate the digester. Given many digester closures have been caused by operational issues and lack of technical skills, this business arrangement may help farmers to utilize manure in a more profitable and sustainable manner.

Fiber recovery from manure management systems represents an opportunity for developing value-added products and generating revenue from secondary markets. Simple mechanical screens and passive systems, such as weeping walls, are often used to collect fiber for reuse or repurposing. Animal bedding is one of the most common reclaimed fiber uses. Composting and anaerobic digestion have been used to disinfect fiber to varying degrees. The value of the recycled fiber helps to offset those systems' costs.

Anaerobically digested and composted dairy fiber may be used as a peat moss substitute in high-quality growth substrates for greenhouse and nursery production. Currently, peat moss usage in horticulture is an estimated 6.8 million tons per year.

A market for biodegradable plant pots (biopots) is emerging. Compostable and plantable biopots aim to replace plastic containers used in horticulture and floriculture. U.S. production totals are approximately 4 billion plastic containers or units annually. Compostable containers have relatively high tensile strength, but they can pose a challenge to plants' root health. In contrast, plantable biopots are designed to decompose once placed in fields and eliminate waste disposal issues.

The study identified several potential Federal programs that could increase incentives for farmers to adopt value-enhancing manure technologies. These include technology cost sharing, support for community digester/composting systems, manure applicator certification, and federally-funded research and development. Manure value can be enhanced through modification of existing renewable energy policy and careful design of nutrient trading regimes.

Market failures create a strong rationale for public policies that promote the development and adoption of environmentally beneficial technologies. Financial assistance programs for promising technologies have both on- and off-farm benefits. The U.S. Environmental Protection Agency and various State environmental agencies have subsidized the transformation of manure into electricity and compressed natural gas. The design of renewable energy and carbon markets will determine the extent to which livestock producers can take advantage of these revenue sources.

Policy design that takes a holistic farming system approach, rather than a crop-by-crop or species-by-species approach, may facilitate the use of manure as a fertilizer. Ideally, policies should account for regional differences in manure supply and demand at the manureshed level. A life cycle analysis framework that quantifies new technologies' air and water quality impacts could help avoid some unintended consequences of regulation or policy.

References

Abdalla, C., L.E. Lanyon, and M.C. Hallberg. 1995. "What We Know about Historical Trends in Firm Location Decisions and Regional Shifts: Policy Issues for an Industrializing Animal Sector," *American Journal of Agricultural Economics* 77:1229–36.

Abdo, H. and R. Ackrill. 2021. "On-Farm Anaerobic Digestion: A Disaggregated Analysis of the Policy Challenges for Greater Uptake," *Energy Policy* 153(June):1122–58.

Ackrill, R. and H. Abdo. 2020. "On-Farm Anaerobic Digestion Uptake Barriers and Required Incentives: A Case Study of the UK East Midlands Region," *Journal of Cleaner Production* 264(August):1217–27.

Adair, E.C., L. Barbieri, K. Schiavone, and H.M. Darby. 2019. "Manure Application Decisions Impact Nitrous Oxide and Carbon Dioxide Emissions during Non-Growing Season Thaws," *Soil Science Society of America Journal* 83(1):163–72.

AgSTAR. 2011. *Recovering Value from Waste: Anaerobic Digester System Basics*, U.S. Environmental Protection Agency, Washington, DC.

Aillery, M., N. Gollehon, R. Johansson, J. Kaplan, and M. Ribaudo. 2005. *Managing Manure To Improve Air and Water Quality,* ERR-9, U.S. Department of Agriculture, Economic Research Service, September 2005.

Al-Ahmed, A. and Inamuddin. 2020. *Advanced Applications of Bio-Degradable Green Composites*, Materials Research Forum LLC, Millersville, PA.

Ali, S., L. McCann, and J. Allspach. 2012b. "Manure Transfers in the Midwest and Factors Affecting Adoption of Manure Testing," *Journal of Agricultural and Applied Economics* 44(4):533–48.

ALL Power Labs. "The Five Processes of Gasification," ALL Power Labs, Berkeley, CA.

Alston, J.M., M.C. Marra, P.G. Pardey, and T.J. Wyatt. 2000. "Research Returns Redux: A Meta-analysis of the Returns to Agricultural R&D," *Australian Journal of Agricultural and Resource Economic*s 44(2):185–215.

Anderson, K, P.A. Moore, J. Martin, and A.J. Ashworth. 2020. "Effect of a New Manure Amendment on Ammonia Emissions from Poultry Litter," *Atmosphere* 11(3):257.

Anderson, R.C., D. Hilborn, and A. Weersink. 2013. "An Economic and Functional Tool for Assessing the Financial Feasibility of Farm-Based Anaerobic Digesters," *Renewable Energy* 51(March):85–92.

Arnold, G. 2020. *Prescription Manure with Growing Crops*, Designer Manure: Customizing Manure Nutrients to Meet Crop Needs.

American Society of Biological and Agricultural Engineers (ASABE). 2019. "Manure Production and Characteristics," ASAE D384.2 MAR2005 (R2010). American Society of Biological and Agricultural Engineers, St. Joseph, MI.

Atienza-Martinez, M., J. Abrego, G. Gea, and F. Marias. 2020. "Pyrolysis of Dairy Cattle Manure: Evolution of Char Characteristics," *Journal of Analytical and Applied Pyrolysis* 145(January):104724.

Avalos Ramirez, A., S. Godbout, F. Léveillée, D. Zegan, and J. Larouche. 2012. "Effect of Temperature and Air Flow Rate on Carbon and Nitrogen Compounds Changes during the Biodrying of Swine Manure in Order to Produce Combustible Biomasses," *Journal of Chemical Technology & Biotechnology* 87(6):831–36.

Barberg, A. E., M. I. Endres, and K. A. Janni. 2007. "Compost Dairy Barns in Minnesota: A Descriptive Study," *Applied Engineering in Agriculture* 23(2):231–38.

Beal, L.J., R.T. Burns, and K.J. Stalder. 1999. "Effect of Anaerobic Digestion on Struvite Production for Nutrient Removal from Swine Waste Prior to Land Application," 1999 ASAE Annual International Meeting, Toronto, Ontario, Canada.

Bernal, M.P., J.A. Alburquerque, and R. Moral. 2009. "Composting of Animal Manures and Chemical Criteria for Compost Maturity Assessment. A Review," *Bioresource Technology* 100 (22):5444–53.

Bewley, J. and R. Black. 2012. "Compost Bedded Pack Barn Design: Features and Management Considerations," ID-206. University of Kentucky Cooperative Extension, Lexington, KY.

BioCycle. 2019. "Biogas To RNG Projects: What, Why And How." BioCycle, Quebec City. March 11, 2019.

Biogas World. 2020. "Showcase Report 2020: Successful Projects of Biogas and Biomethane Suppliers • BiogasWorld," BiogasWorld, Quebec City, Quebec, Canada. 2020.

Bosch, D., M. Zhu, and E. Kornegay. 1997. "Economic Returns from Reducing Poultry Litter Phosphorus with Microbial Phytase," *Journal of Agricultural and Applied Economics* 29(2):255–66.

Bowers, K. E., and P. W. Westerman. 2005. "Performance of Cone-Shaped Fluidized Bed Struvite Crystallizers in Removing Phosphorus from Wastewater," *Transactions of the ASAE* 48(3):1227–34.

Buchanan, J.R., C.R. Mote, and R.B. Robinson. 1994. "Thermodynamics of Struvite Formation," *Transactions of the ASAE* 37(2):617–21.

Burg, V., K.G. Troitzsch, D. Akyol, U. Baier, S. Hellweg, and O. Thees. 2021. "Farmer's Willingness to Adopt Private and Collective Biogas Facilities: An Agent-Based Modeling Approach," *Resources, Conservation and Recycling* 167(April):105400.

California Air Resources Board. 2020. "Credit Generation for Reduction of Methane Emissions from Manure Management Operations," California Air Resources Board, Sacramento, CA.

California Air Resources Board. 2021a. "Cap-and-Trade Program," California Air Resources Board, Sacramento, California.

California Air Resources Board. 2021b. "Low Carbon Fuel Standard," California Air Resources Board, Sacramento, California.

California Air Resources Board. 2021. "LCFS Pathway Certified Carbon Intensities," California Air Resources Board, Sacramento, CA.

California Department of Food and Agriculture. 2021a. "Alternative Manure Management Practices," California Department of Food and Agriculture, Office of Environmental Farming and Innovation, Sacramento, California.

California Department of Food and Agriculture. 2021b. "Dairy Digester Research and Development Program," California Department of Food and Agriculture, Office of Environmental Farming and Innovation, Sacramento, California.

Campos, J.L., D. Crutchik, Ó. Franchi, J.P. Pavissich, M. Belmonte, A. Pedrouso, A. Mosquera-Corral, and Á. Val del Río. 2019. "Nitrogen and Phosphorus Recovery From Anaerobically Pretreated Agro-Food Wastes: A Review," *Frontiers in Sustainable Food Systems* 2:91.

Canter, T., T. Lim, and J. Zulovich. 2021. "Nutrient Recovery System for Dairy Farms: Dissolved Air Floatation and Multi-Disk Pres,." EQ-303. University of Missouri Extension, Colombia, MO.

Cantrell, K.B., P.G. Hunt, M. Uchimiya, J.M. Novak, and K.S. Ro. 2012. "Impact of Pyrolysis Temperature and Manure Source on Physicochemical Characteristics of Biochar," *Bioresource Technology* 107(March): 419–28.

Cantrell, K., K. Ro, D. Mahajan, M. Anjom, and P.G. Hunt. 2007. "Role of Thermochemical Conversion in Livestock Waste-to-Energy Treatments: Obstacles and Opportunities," *Industrial & Engineering Chemistry Research* 46(26):8918–27.

Capano, G. and M. Howlett. 2020. "The Knowns and Unknowns of Policy Instrument Analysis: Policy Tools and the Current Research Agenda on Policy Mixes," *SAGE Open* 10(1):215824401990056.

Carlile, W.R., C. Cattivello, and P. Zaccheo. 2015. "Organic Growing Media: Constituents and Properties," *Vadose Zone Journal*, April 2015.

Carlson, M., F. Forcella, S. Wortman, D. Clay, and S.A. Clay. 2020. "Organic Fertilizer Abrasive Grits Increase Soil Available Nitrogen, Plant Height, and Biomass," *Agrosystems, Geosciences & Environment* 3(1).

Carr, P.M., M.A. Cavigelli, H. Darby, K. Delate, J.O. Eberly, H.K. Fryer, G.G. Gramig, J.R. Heckman, E.B. Mallory, J.R. Reeve, E.M. Green, 2020. "Green and Animal Manure Use in Organic Field Crop Systems," *Agronomy Journa*l 112(2):648–74.

Castrodeza, C., P. Lara, and T. Peña. 2005. "Multicriteria Fractional Model for Feed Formulation: Economic, Nutritional and Environmental Criteria," *Agricultural Systems* 86(1):76–96.

Chastain, J.P., and J.J. Camberato. 2004. "Dairy Manure Production and Nutrient Content," In *Chapter 3a, CAMM Dairy Training Manual*. Clemson University, Cooperative Extension, Clemson, SC.

Chastain, J.P., J.J Camberato, and P. Skewes. 2004. "Poultry Manure Production and Nutrient Content," In *Chapter 3b, CAMM Poultry Training Manual*. Clemson University, Cooperative Extension, Clemson, SC.

Chen, H., M.K. Awasthi, T. Liu, J. Zhao, X. Ren, M. Wang, Y. Duan, S.K. Awasthi, and Z. Zhang. 2018. "Influence of Clay as Additive on Greenhouse Gases Emission and Maturity Evaluation during Chicken Manure Composting," *Bioresource Technology*, 266(June):82–88.

Chen, L. and H. Neibling. 2014. "Anaerobic Digestion Basics," CIS 1215. University of Idaho Extension, Moscow, ID.

Chen, R., R. Li, L. Deitz, Y. Liu, R.J. Stevenson, and W. Liao. 2012. "Freshwater Algal Cultivation with Animal Waste for Nutrient Removal and Biomass Production," *Biomass and Bioenergy* 39(April):128–38.

Chowdhury, R., and F. Freire. 2015. "Bioenergy Production from Algae Using Dairy Manure as a Nutrient Source: Life Cycle Energy and Greenhouse Gas Emission Analysis," *Applied Energy* 154(September):1112–21.

Codling, E.E., R.L. Chaney, and C.L. Mulchi. 2000. "Use of Aluminum- and Iron-Rich Residues to Immobilize Phosphorus in Poultry Litter and Litter-Amended Soils," *Journal of Environmental Quality* 29(6):1924–31.

Cooney, C.L. 2005. “Solid Liquid Separation: Centrifugation,” Presented at the Downstream Processing Course, August 1, MIT Professional Institute, Cambridge, MA.

Cote, P., Z. Alam, and J. Penny. 2012. “Hollow Fiber Membrane Life in Membrane Bioreactors (MBR),” *Desalination* 288(March):145–51.

Cowley, C. and W.B. Brorsen. 2018. “The Hurdles to Greater Adoption of Anaerobic Digesters,” *Agricultural and Resource Economics Review* 47(1):132–57.

Dell, C.J., J.J. Meisinger, and D.B. Beegle. 2011. “Subsurface Application of Manures Slurries for Conservation Tillage and Pasture Soils and Their Impact on the Nitrogen Balance,” *Journal of Environmental Quality* 40(2):352–61.

Deutsch, S. 2007. *A Burning Answer for Manure*, National Hog Farmer, September 15, 2007.

Domingo, N.G., S. Balasubramanian, S.K. Thakrar, M.A. Clark, P.J. Adams, J.D. Marshall, N.Z. Muller, S.N. Pandis, S. Polasky, A.L. Robinson, C.W. Tessum, D. Tilman, P. Tschofen, J.D. Hill. 2021. “Air Quality–Related Health Damages of Food,” *Proceedings of the National Academy of Sciences* 118(20):e2013637118.

Eghball, B. and G. Lesoing. 2000. “Viability of Weed Seeds Following Manure Windrow Composting” *Compost Science and Utilization* 8(1):46–53.

EnergyWorks. 2013. “Gettysburg Energy & Nutrient Recovery Facility.” Energy Works, Annapolis, MD.

Escudero, J.D. 2017. *Challenges and Opportunities for Increased Production of Renewable Natural Gas (RNG)*, Presented at the Coalition for Renewable Natural Gas, September 26, Broomfield, CO.

Everwood Farm. n.d. “Vermicomposting Equipment.” Everwood Farm, Yamhill, OR.

Fallert, R.F. 1981. “Milk Pricing – Past, Present, the 1980’s,” *Journal of Dairy Science* 64(6):1105–12.

Fang, F., K.W. Easter, and P.L. Brezonik. 2005. “Point-Nonpoint Source Water Quality Trading: A Case Study in the Minnesota River Basin,” *Journal of the American Water Resources Association* June 2005:645–58.

Fangueiro, D., M. Hjorth, and F. Gioelli. 2015. “Acidification of Animal Slurry–A Review,” *Journal of Environmental Management* 149(February):46–56.

Farm Show Magazine. 2008. “Manure Drying System Fuels Itself,” Farm Show Magazine, Lakeville, MN.

Fasaei, F., J.H. Bitter, P.M. Slegers, and A.J.B. van Boxtel. 2018. “Techno-Economic Evaluation of Microalgae Harvesting and Dewatering Systems,” *Algal Research* 31(April):347–62.

Feder, G., R.E. Just, and D. Zilberman. 1985. “Adoption of Agricultural Innovations in Developing Countries: A Survey,” *Economic Development and Cultural Change* 33(2):255–98.

Feldmann, J., V. Gauthier, M. Monast, M. Rupp, and B. Aasmundstad. 2019. *Innovative State-Led Efforts to Finance Agricultural Conservation*, Environmental Defense Fund and The National Association of State Departments of Agriculture, New York, NY and Arlington, VA.

“Fibrominn.” 2020. In *Wikipedia*.

Fleming, P.M., E. Lichtenberg, and D.A. Newburn. 2020. "Water Quality Trading in the Presence of Conservation Subsidies," *Land Economics* 96(4):552–72.

Fleming, R.A. 1999. "The Economic Impact of Setback Requirements on Land Application of Manure," *Land Economics* 75(4):579–91.

Fleming, R.A., B.A. Babcock, and E. Wang. 1998. "Resource or Waste? The Economics of Swine Manure Storage and Management," *Review of Agricultural Economics* 20(1):96–113.

Fleming, R.A. and J.D. Long. 2002. "Measuring the Cost of Restricting Access to Cropland for Manure Nutrient Management," *Agronomy Journal* 94(1):57–64.

Fuentes, V. 2009. Method and System for Inoculating Bacteria in Contaminated Water Using Earthworm Humus. USPTO 7,540,690, filed February 2, 2007, and issued June 2, 2009.

Gburek, W.J., and A.N. Sharpley. 1998. "Hydrologic Controls on Phosphorus Loss from Upland Agricultural Watersheds," *Journal of Environmental Quality* 27(2):267–77.

Gedikoglu, H., L. McCann, and G. Artz. 2011. "Impact of Off-Farm Employment Effects on Adoption of Conservation Practices," *Agricultural and Resource Economics Review* 40(2):293–306.

Gedikoglu, H., and L. McCann. 2012. "Adoption of Win-Win, Environment-Oriented and Profit-Oriented Practices." *Journal of Soil and Water Conservation* 67(3):218–27.

Ghebremichael, L.T., T.L. Veith, and J.M. Hamlett. 2013. "Integrated Watershed- and Farm-Scale Modeling Framework for Targeting Critical Source Areas While Maintaining Farm Economic Viability," *Journal of Environmental Management* 114(January):381–94.

Gollehon, N.R, R.L Kellogg, and D.C. Moffitt. 2016. "Estimates of Recoverable and Non-Recoverable Manure Nutrients Based on the Census of Agriculture—2012," U.S. Department of Agriculture, Natural Resource Conservation Service, June 2016.

Greene, P. 2019. "101 for Low Carbon Fuel Standard," *BioCycle*. March 11, 2019.

Hall, C.R., B.L. Campbell, B.K. Behe, C. Yue, R.G. Lopez, and J.H. Dennis. 2010. "The Appeal of Biodegradable Packaging to Floral Consumers," *HortScience* 45(4):583–91.

Hallbar Consulting. "Evaluation of Nutrient Recovery Technologies," Hallbar Consulting, Vancouver, British Columbia, Canada.

Hamilton, D. 2019. *Farm Energy: Types of Anaerobic Digestion*, Extension.org, Kansas City, MO.

Hamilton, D., M.E. Murie, A.M.A. Khan, and P.M. Ndegwa. 2008. *Vermicomposting of Poultry Litter: Process Optimization*, In American Society of Agricultural and Biological Engineers, Providence, RI.

Hanson, J.C. 2016. *Manure Treatment Technologies*, CBP/TRS-311-16. Chesapeake Bay Program, Annapolis, MD.

Hao, X. and Z. He. 2019. "Pelletizing Animal Manures for On- and Off-Farm Use." In *Animal Manure: Production, Characteristics, Environmental Concerns and Management*, edited by H.M. Waldrip, P.H. Pagliari, and Z. He, 323–44. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, WI.

Haren, M.V. and R. Fleming. 2005. *Electricity and Heat Production Using Biogas from the Anaerobic Digestion of Livestock Manure- Literature Review*, Report to Ontario Ministry of Agriculture, Food and Rural Affairs, Guelph, Ontario, Canada.

Harris, B.A., W.J. Florkowski, and S.V. Pennisi. 2020. "Horticulture Industry Adoption of Biodegradable Containers," *HortTechnology* 30(3):372–84.

Hay, J.C., R.D. Kuchenrither, Richard D. 1991. "Fundamentals and Application of Windrow Composting," *Journal of Environmental Engineering* 116(4):746–63.

Hergert, G., R. Nielsen, and J. Margheim. 2015. *Fertilizer History*, University of Nebraska, Institute of Agriculture and Natural Resources, Lincoln, NE.

Hicks, K. 2020. "Agronomic Services – Waste/Compost Analysis." North Carolina Department of Agriculture and Consumer Services, Raleigh, NC.

Hille, E., and P. Möbius. 2019. "Environmental Policy, Innovation, and Productivity Growth: Controlling the Effects of Regulation and Endogeneity," *Environmental and Resource Economics* 73(4):1315–55.

Hirshey, G. (2009, February 26). From Tons of Manure, a Growth Industry, *The New York Times*.

Hoffman, L. and A. Baker. 2010. *Market Issues and Prospects for U.S. Distillers' Grains Supply, Use, and Price Relationships*, FDS-10K-01. U.S. Department of Agriculture, Economic Research Service.

Huang, G.F., Q.T. Wu, J.W.C. Wong, and B.B. Nagar. 2006a. "Transformation of Organic Matter during Co-Composting of Pig Manure with Sawdust," *Bioresource Technology* 97(15):1834–42.

Jaffe, A.B., R.G. Newell, and R.N. Stavins. 2005. "A Tale of Two Market Failures: Technology and Environmental Policy," *Ecological Economics* 54(2–3):164–74.

Janni, K.A., M.I. Endres, J.K. Reneau, and W.W. Schoper. 2007. "Compost Dairy Barn Layout and Management Recommendations," *Applied Engineering in Agriculture* 23(1):97–102.

Jindo, K., M.A. Sánchez-Monedero, T. Hernández, C. García, T. Furukawa, K. Matsumoto, T. Sonoki, and F. Bastida. 2012. "Biochar Influences the Microbial Community Structure during Manure Composting with Agricultural Wastes," *Science of The Total Environment* 416(February):476–81.

Jones, J. 2006. "Hog Farming." In *Encyclopedia of North Carolina*. University of North Carolina, Chapel Hill, NC.

Kai, P., P. Pedersen, J.E. Jensen, M.N. Hansen, and S.G. Sommer. 2008. "A Whole-Farm Assessment of the Efficacy of Slurry Acidification in Reducing Ammonia Emissions," *European Journal of Agronomy* 28(2):148–54.

Kebreab, E., A. Liedke, D. Caro, S. Deimling, M. Binder, and M. Finkbeiner. 2016. "Environmental Impact of Using Specialty Feed Ingredients in Swine and Poultry Production: A Life Cycle Assessment," *Journal of Animal Science* 94(6):2664–81.

Key, N., W.D. McBride, M. Ribaudo, and S. Sneeringer. 2011. *Trends and Developments in Hog Manure Management: 1998–2009*, EIB-181. U.S. Department of Agriculture, Economic Research Service.

Key, N., and S. Sneeringer. 2011a. *Climate Change Policy and the Adoption of Methane Digesters on Livestock Operations*, ERR-111. U.S. Department of Agriculture, Economic Research Service.

Key, N. and S. Sneeringer. 2011b. “Carbon Markets and Methane Digesters: Potential Implications for the Dairy Sector,” *Journal of Agricultural and Applied Economics*, 43(4): 1–22.

Key, N. and S. Sneeringer. 2012. “Carbon Emissions, Renewable Electricity and Profits: Comparing Alternative Policies to Promote Anaerobic Digesters on Dairies,” *Agricultural and Resource Economics Review*. 41(2):139–157.

Kirk, D., and M. Gould. 2019. *Farm Energy: Uses of Solids and By-Products of Anaerobic Digestion*, Extension.org, Kansas City, MO.

Knight, R. 2020. *Beef Sector at a Glance*, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Koller, F., and O.B. Jesness. 1940. *Trends in the Minnesota Dairy Industry*, Agricultural Experiment Station Bulletin 346. University of Minnesota, Minneapolis, MN.

Konyar, K. and K. Knapp. 1990. “Dynamic Regional Analysis of the California Alfalfa Market with Government Policy Impacts,” *Western Journal of Agricultural Economics* 15(1):22–32.

Kumar, K., S.K. Mishra, A. Shrivastav, M.S. Park, and J. Yang. 2015. “Recent Trends in the Mass Cultivation of Algae in Raceway Ponds,” *Renewable and Sustainable Energy Reviews* 51(November):875–85.

Kumar, S., S. Negi, A. Mandpe, R.V. Singh, and A. Hussain. 2018. “Rapid Composting Techniques in Indian Context and Utilization of Black Soldier Fly for Enhanced Decomposition of Biodegradable Wastes - A Comprehensive Review” *Journal of Environmental Management* 227(December):189–99.

Labatut, R.A. and C.A. Gooch. 2012. *Monitoring of Anaerobic Digestion Process to Optimize Performance And Prevent System Failure*, Cornell University, Department of Biological and Environmental Engineering. Cornell University, Ithaca, NY.

Lamont, J.R. 2015. *Evaluating Anaerobically Digested Dairy Fiber as a Substitute for Peat in Container Production and Nutrient Availability from Organic Fertilizers and Amendments*, University of Connecticut, Storrs, CT.

Leach, K.A., S.C. Archer, J.E. Breen, M.J. Green, I.C. Ohnstad, S. Tuer, and A.J. Bradley. 2015. “Recycling Manure as Cow Bedding: Potential Benefits and Risks for UK Dairy Farms,” *The Veterinary Journal* 206(2):123–30.

Leso, L., M. Barbari, M.A. Lopes, F.A. Damasceno, P. Galama, J.L. Taraba, and A. Kuipers. 2020. “Compost-Bedded Pack Barns for Dairy Cows,” *Journal of Dairy Science* 103(2):1072–99.

Lewthwaite, G.R. 1964. “Wisconsin Cheese and Farm Type: A Locational Hypothesis,” *Economic Geography* 40(2):95–112.

Li, H., D. Mehmood, E. Thorin, and Z. Yu. 2016. “Biomethane Production Via Anaerobic Digestion and Biomass Gasification,” *Energy Procedi*a, 105:1172–77.

Li, Q., L. Zheng, N. Qiu, H. Cai, J.K. Tomberlin, and Z. Yu. 2011. “Bioconversion of Dairy Manure by Black Soldier Fly (Diptera: Stratiomyidae) for Biodiesel and Sugar Production,” *Waste Management* 31(6):1316–20.

Li, Y. and N.S. Mattson. 2019. “Effect of Organic Fertilizer Source and Rate on Growth and Nutrient Leachate Profile of Greenhouse-Grown Cucumber,” *HortTechnology* 29(4):450–56.

Lichtenberg, E., D. Parker, and L. Lynch. 2002. *Economic Value of Poultry Litter Supplies In Alternative Uses*, Policy Analysis Report Number 02-02. University of Maryland, Center for Agricultural and Natural Resource Policy, College Park, MD.

Lipson, J. 2019. *Clean Fuels Program Comparison Chart: California, Oregon, and Proposed Washington Programs*, Washington House Environment and Energy Committee, Olympia, WA.

Lorimor, J., C. Fulhage, R. Zhang, T. Funk, R. Sheffield, D.C. Sheppard, and G.L. Newton. 2006. "Manure Management Strategies and Technologies," in *Animal Agriculture and the Environment*, 409–34. National Center for Manure and Animal Waste Management, Raleigh, NC.

Lorimor, J., W. Powers, and A. Sutton. 2000. *Manure Characteristics*, MWPS-18, Section 1. Midwest Plan Service, Ames, IA.

Lorimor, J., W. Powers and A. Sutton. 2004. *Manure Characteristics. Midwest Plan Service-18*, Section 1, MWPS-18 (1993), Section 1, Tables 8, 9, 11.

Ma, J., C.E. Kruger, J. Jensen, C. Frear, R.L. Hummel, and G. Yorgey. 2016. *Digested Fiber Solids: Methods for Adding Value*, FS235E. Washington State University Extension, Pullman, WA.

Ma, Q., K.P. Paudel, D. Bhandari, C. Theegala, and M. Cisneros. 2019. "Implications of Poultry Litter Usage for Electricity Production," *Waste Management* 95(July):493–503.

MacDonald, J.M. 2008. *Fertilizer from Chicken Litter*, Manure Manager, Simcoe, Ontario, Canada.

MacDonald, J.M. 2014. *Technology, Organization, and Financial Performance in U.S. Broiler Production*. EIB-126. U.S. Department of Agriculture, Economic Research Service.

MacDonald, J.M. 2020. "Tracking the Consolidation of U.S. Agriculture," *Applied Economic Perspectives and Policy* 00(00):1–19.

MacDonald, J.M.. 2020. "Tracking Consolidation in U.S. Agriculture," *Amber Waves*, U.S. Department of Agriculture, Economic Research Service, February 2020.

MacDonald, J.M., R.A. Hoppe, and D. Newton. 2018. *Three Decades of Consolidation in U.S. Agriculture*, EIB-189, U.S. Department of Agriculture, Economic Research Service, March 2018.

MacDonald, J.M., M.O. Ribaudo, M.J. Livingston, J. Beckman, and W. Huang. 2009. *Manure Use for Fertilizer and for Energy: Report to Congress*, U.S. Department of Agriculture, Economic Research Service, June 2019.

Maguire, R.O., P.J.A. Kleinman, C.J. Dell, D.B. Beegle, R.C. Brandt, J.M. McGrath, and Q.M. Ketterings. 2011. "Manure Application Technology in Reduced Tillage and Forage Systems: A Review," *Journal of Environmental Quality* 40(2):292–301.

Makádi, M., A. Tomócsik, and V. Orosz. 2012. "Digestate: a new nutrient source–review." Chapter in Biogas, ECDC-TCDC Services, Denmark, pages 295–312.

Mansfield, E. 1961. "Technical Change and the Rate of Imitation," *Econometrica* 29(4):741.

Martin, S. 1993. Advanced Industrial Economics, Massachusetts: Blackwell Publishers.

Martinez, S.W. and K. Zering. 2004. *Pork Quality and the Role of Market Organization*, AER-835. U.S. Department of Agriculture, Economic Research Service, October 2004.

Martín-Hernández, E., G.J. Ruiz-Mercado, and M. Martín. 2020. "Model-Driven Spatial Evaluation of Nutrient Recovery from Livestock Leachate for Struvite Production," *Journal of Environmental Management* 271(2020):110967.

Maryland Department of Agriculture. 2020. "Department Awards Animal Waste Technology Grant to Biorefinery Project in Wicomico County," Maryland Department of Agriculture, Annapolis, MD.

Maryland Department of Agriculture. n.d. "Manure Transport Program," Maryland Department of Agriculture: Manure Transport Program, Annapolis, MD. (accessed October 7, 2021).

Massey, R.E., and H. Gedikoglu. 2021. "Manure Application Rules and Environmental Considerations," *Agricultural Water Management* 243(January):106512.

Mazeika, R., G. Staugaitis, and J. Baltrusaitis. 2016. "Engineered Pelletized Organo-Mineral Fertilizers (OMF) from Poultry Manure, Diammonium Phosphate and Potassium Chloride," *ACS Sustainable Chemistry & Engineering* 4(4):2279–85.

McCann, L. 2009. "Transaction Costs of Environmental Policies and Returns to Scale: The Case of Comprehensive Nutrient Management Plans," *Review of Agricultural Economics* 31(3):561–73.

McCann, L., C. Abdalla, M. Jenner, and R. Massey. 2005. "Improved Manure Management and Utilization: A Systems Approach," *Renewable Agriculture and Food Systems* 20(3):127–35.

McCann, L., H. Gedikoglu, B. Broz, J. Lory, and R. Massey. 2015. "Effects of Observability and Complexity on Farmers' Adoption of Environmental Practices," *Journal of Environmental Planning and Management* 58(8):1346–62.

McConnell, M. 2021. *U.S. Bioenergy Statistics*, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

McGrath, J.M., J.T. Sims, R.O. Maguire, W.W. Saylor, C.R. Angel, and B.L. Turner. 2005. "Broiler Diet Modification and Litter Storage: Impacts on Phosphorus in Litters, Soils, and Runoff," *Journal of Environmental Quality* 34(5):1896–1909.

McKendry, P. 2002. "Energy Production from Biomass (Part 2): Conversion Technologies," *Bioresource Technology*, Reviews Issue, 83(1):47–54.

Meyer, D., P.L. Ristow, and M. Lie. 2007. "Particle Size and Nutrient Distribution in Fresh Dairy Manure," *Applied Engineering in Agriculture* 23(1):113–18.

Mieldažys, R., E. Jotautienė, A. Pocius, and A. Jasinskas. 2016. "Analysis of Organic Agricultural Waste Usage for Fertilizer Production," *Agronomy Research* 14(1):143–49.

Mieldažys, R., E. Jotautienė, and A. Jasinskas. 2019. "The Opportunities of Sustainable Biomass Ashes and Poultry Manure Recycling for Granulated Fertilizers," *Sustainability* 11:4466.

Milliron, R.A., H.D. Karsten, and D.B. Beegle. 2019. "Influence of Dairy Slurry Manure Application Method, Fall Application-Timing, and Winter Rye Management on Nitrogen Conservation," *Agronomy Journal* 111(3):995–1009.

Misra, R.V., R.N. Roy, and H. Hiraoka. 2003. "Chapter 3. Large-Scale Composting," in *On-Farm Composting Methods*. Rome: Food and Agriculture Organization of the United Nations.

Modderman, C. 2019. "Composting With or Without Additives," in *Animal Manure: Production, Characteristics, Environmental Concerns and Management*, eds H.M. Waldrip, P.H. Pagliari, and Z. He, 323–44. Madison, WI, USA: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Möller, K. and T. Müller. 2012. "Effects of Anaerobic Digestion on Digestate Nutrient Availability and Crop Growth: A Review," *Engineering in Life Sciences* 12(3):242–57.

Moore, P.A., and D.R. Edwards. 2007. "Long-Term Effects of Poultry Litter, Alum-Treated Litter, and Ammonium Nitrate on Phosphorus Availability in Soils," *Journal of Environmental Quality* 36(1):163–74.

Moore, P.A., and D.M. Miller. 1994. "Decreasing Phosphorus Solubility in Poultry Litter with Aluminum, Calcium, and Iron Amendments," *Journal of Environmental Quality* 23(2):325–30.

Moore, P.A., S. Watkins, D.C. Carmen, and P.B. DeLaune. 2004. *Treating Poultry Litter with Alum*. FSA8003. University of Arkansas Cooperative Extension, Fayetteville, AR.

Moore, P.A., T.C. Daniel, and D.R. Edwards. 2000. "Reducing Phosphorus Runoff and Inhibiting Ammonia Loss from Poultry Manure with Aluminum Sulfate." *Journal of Environmental Quality* 29(1):37–49.

Moore, P.A., T.C. Daniel, and D.R. Edwards. 1999. "Reducing Phosphorus Runoff and Improving Poultry Production with Alum," *Poultry Science* 78(5):692–98.

Moore, P.A. 2011. "Improving the Sustainability of Animal Agriculture by Treating Manure with Alum," in *Environmental Chemistry of Animal Manure*, 349–81. Hauppauge, NY: Nova Science Publishers, Inc.

Motallebi, M., D.L. Hoag, A. Tasdighi, M. Arabi, and D.L. Osmond. 2017. "An Economic Inquisition of Water Quality Trading Programs, with a Case Study of Jordan Lake, N.C.," *Journal of Environmental Management* 193(May):483–90.

Mukhtar, S., M.S. Borhan, and J. Beseda II. 2011. "Evaluation of a Weeping Wall Solid-Liquid Separation System for Flushed Dairy Manure," *Applied Engineering in Agriculture* 27(1):135–42.

Mulbry, W., E.K. Westhead, C. Pizarro, and L. Sikora. 2005. "Recycling of Manure Nutrients: Use of Algal Biomass from Dairy Manure Treatment as a Slow Release Fertilizer," *Bioresource Technology* 96(4):451–58.

Mulkey, A., telephone interview with author, February 10, 2021.

Nambuthiri, S., A. Fulcher, A.K. Koeser, R. Geneve, and G. Niu. 2015. "Moving Toward Sustainability with Alternative Containers for Greenhouse and Nursery Crop Production: A Review and Research Update," *HortTechnology* 25(1):8–16.

National Chicken Council. 2020. "NCC Animal Welfare Guidelines and Audit Checklist for Broilers," National Chicken Council, Washington, DC.

National Research Council. 2012. *Nutrient Requirements of Swine, 11th Edition*. Washington, D.C.: The National Academies Press.

Nehring, R. 2020. "Fertilizer Rates Increase in the Top 10 Hog States, But Excess Nutrient Levels Are Falling," *Amber Waves*, U.S. Department of Agriculture, Economic Research Service, August 3, 2020.

Norwood, F.B., and J. Chvosta. 2005. "Phosphorus-Based Applications of Livestock Manure and the Law of Unintended Consequences," *Journal of Agricultural and Applied Economics* 37:79–90.

Nova Pinedo, M.L., N. Ferronato, M. Ragazzi, and V. Torretta. 2019. "Vermicomposting Process for Treating Animal Slurry in Latin American Rural Areas," *Waste Management & Research* 37(6):611–20.

Nunez, J., and L. McCann. 2008. "Determinants of Manure Application by Crop Farmers," *Journal of Soil and Water Conservation* 63(5):312–21.

NYSERDA. 2014. "Anaerobic Digester Business Model and Financing Options for Dairy Farms in New York State," New York State Energy Research and Development Authority, Report 14–30. May.

O'Donoghue, E.J., R.A. Hoppe, D.E. Banker, R. Ebel, K. Fuglie, P. Korb, M. Livingston, C. Nickerson, and C. Sandretto. 2011. *The Changing Organization of U.S. Farming*, EIB-88. U.S. Department of Agriculture, Economic Research Service, December 2011.

"OptiPlate: High Capacity Steel Plate Manure Drying System." n.d. Commercial. Big Dutchman North America (blog). Accessed November 2, 2020.

Osmonics, Inc. 2012. "Water–What Matters?," Osmonics, Inc., Cleaning Technologies Group, Minnetonka, MN.

"Panda Energy International." 2021. In *Wikipedia*.

Pannell, D.J., J.M. Alston, S. Jeffrey, Y.M. Buckley, P. Vesk, J.R. Rhodes, E. McDonald-Madden, S. Nally, G. Goucher, and T. Thamo. 2018. "Policy-Oriented Environmental Research: What Is It Worth?," *Environmental Science & Policy* 86(August):64–71.

Pannell, D.J., G.R. Marshall, N. Barr, A. Curtis, F. Vanclay, and R. Wilkinson. 2006. "Understanding and Promoting Adoption of Conservation Practices by Rural Landholders," *Australian Journal of Experimental Agriculture* 46(11):1407–24.

Paudel, K.P., M. Adhikari, and N.R. Martin. 2004. "Evaluation of Broiler Litter Transportation in Northern Alabama, USA," *Journal of Environmental Management* 73(1):15–23.

Paudel, K.P., K. Bhattarai, W.M. Gauthier, and L.M. Hall. 2009. "Geographic Information Systems (GIS) Based Model of Dairy Manure Transportation and Application with Environmental Quality Consideration," *Waste Management* 29(5):1634–43.

Pelaez-Samaniego, M.R., R.L. Hummel, W. Liao, J. Ma, J. Jensen, C. Kruger, and C. Frear. 2017. "Approaches for Adding Value to Anaerobically Digested Dairy Fiber," *Renewable and Sustainable Energy Reviews* 72(May):254–68.

Penn, C. and H. Zhang. 2017. *Alum-Treated Poultry Litter as a Fertilizer Source*, PSS-2254. Oklahoma State University Extension, Stillwater, OK.

Pennsylvania Department of Environmental Protection. 2012. "Nutrient Trading Program," Pennsylvania Department of Environmental Protection, Harrisburg, PA.

Perry, A. 2014. *USDA Researchers Simplify Pyrolysis Processes for Bio-Oil Production*, Manure Manager, Simcoe, Ontario, Canada, July 8, 2014.

Peterson, K.H. 2002. Geographic Changes in U.S. Dairy Production, in *Annual Meeting of the American Agricultural Economics Association*. Long Beach, CA.

Phasey, J. 2020. *Method to Improve the Dewatering of Farm Waste Sludges*, 2020/Patent Number 0223731 A1, issued July 16, 2020.

Pokhrel, B.K., and K.P. Paudel. 2019. "Assessing the Efficiency of Alternative Best Management Practices to Reduce Nonpoint Source Pollution in a Rural Watershed Located in Louisiana, USA," *Water* 11(8):1714.

Pöschl, M., S. Ward, and P. Owende. 2010. "Evaluation of Energy Efficiency of Various Biogas Production and Utilization Pathways," *Applied Energy* 87(11):3305–21.

Potts, L.G.A. and D.J. Martin. 2009. "Anaerobic Digestion, Gasification, and Pyrolysis," in *Encyclopedia of Life Support Systems*. United Nations Educational Scientific and Cultural Organization, Paris, France.

Powar, M.M., V.S. Kore, S.V. Kore, and G.S. Kulkarni. 2013. "Review on Applications of UASB Technology for Wastewater Treatment," *International Journal of Advanced Science, Engineering and Technology* 2(2):125–33.

Prasai, T.P., K.B. Walsh, D.J. Midmore, B.E.H. Jones, and S.P. Bhattarai. 2018. "Manure from Biochar, Bentonite and Zeolite Feed Supplemented Poultry: Moisture Retention and Granulation Properties," *Journal of Environmental Management* 216(June):82–88.

Preston, W., telephone interview with author, January 30, 2021.

Prokopy, L.S., K. Floress, J.G. Arbuckle, S.P. Church, F.R. Eanes, Y. Gao, B.M. Gramig, P. Ranjan, and A.S. Singh. 2019. "Adoption of Agricultural Conservation Practices in the United States: Evidence from 35 Years of Quantitative Literature," *Journal of Soil and Water Conservation* 74(5):520–34.

Putman, B., G. Thoma, J. Burek, and M. Matlock. 2017. "A Retrospective Analysis of the United States Poultry Industry: 1965 Compared with 2010," *Agricultural Systems* 157(October):107–17.

Ranga R.A., G.A. Ravishankar, and R. Sarada. 2012. "Cultivation of Green Alga Botryococcus Braunii in Raceway, Circular Ponds under Outdoor Conditions and Its Growth, Hydrocarbon Production," *Bioresource Technology* 123(November):528–33.

Reindl, J. 2007. "Phosphorous Removal from Wastewater and Manure through Struvite Formation: An Annotated Bibliography," Dane County Department of Highway, Transportation, and Public Works, Madison, WI.

Ribaudo, M., and L. McCann. 2012. *Accounting for Transaction Costs in Point/Nonpoint Water Quality Trading Programs in the Chesapeake Bay Watershed*, Agricultural and Applied Economics Association Annual Meeting, August 12-14, 2012, Seattle, WA.

Ribaudo, M., N. Key, and S. Sneeringer. 2017. "The Potential Role for a Nitrogen Compliance Policy in Mitigating Gulf Hypoxia," *Applied Economic Perspectives and Policy* 39(3):458–78.

Ribaudo, M.O., and J. Gottlieb. 2011. "Point-Nonpoint Trading−Can It Work?," *Journal of the American Water Resources Association* 47(1):5–14.

Rodhe, L., and M.A. Halling. 2015. "Grassland Yield Response to Knife/Tine Slurry Injection Equipment – Benefit or Crop Damage?," *Grass and Forage Science* 70(2):255–67.

Rogers, E.M. 2003. *Diffusion of Innovations: 3rd Edition*. New York: Free Press.

Rojas, O.J., Y. Liu, and H.H. Stein. 2013. "Phosphorus Digestibility and Concentration of Digestible and Metabolizable Energy in Corn, Corn Coproducts, and Bakery Meal Fed to Growing Pigs," *Journal of Animal Science* 91(11):5326–35.

Ross, C.C., B.M. Smith, and G.E. Valentine. 2000. "Rethinking Dissolved Air Flotation (DAF) Design for Industrial Pretreatment," *Proceedings of the Water Environment Federation* 2000(5):43–56.

Rotz, C.A., P.J.A. Kleinman, C.J. Dell, T.L. Veith, and D.B. Beegle. 2011. "Environmental and Economic Comparisons of Manure Application Methods in Farming Systems," *Journal of Environmental Quality* 40(2):438–48.

Russelle, M.P., Martin H. Entz, and Alan J. Franzluebbers. 2007. "Reconsidering Integrated Crop-Livestock Systems in North America," *Agronomy Journal* 99(2):325–34.

S.1251−117th Congress (2021−22). Growing Climate Solutions Act of 2021. (2021, April 22).

Saha, G.K., R. Cibin, H. Elliott, H. Gall, J. Shortle, and D. Alber. 2018. "Geospatial Landscape Analysis for Livestock Manure Management in Western Pennsylvania," in *ASABE 2018 Annual International Meeting*, American Society of Agricultural and Biological Engineers, Detroit, MI.

Sahoo, N.K., S.K. Gupta, I. Rawat, F.A. Ansari, P. Singh, S.N. Naik, and F. Bux. 2017. "Sustainable Dewatering and Drying of Self-Flocculating Microalgae and Study of Cake Properties," *Journal of Cleaner Production* 159(August):248–56.

Scarlat, N., F. Fahl, J. Dallemand, F. Monforti, and V. Motola. 2018. "A Spatial Analysis of Biogas Potential from Manure in Europe," *Renewable and Sustainable Energy Reviews* 94(October):915–30.

Schott, L.R., and A.M. Schmidt. 2017. "Synthesis of Short-and Long-Term Studies Reporting Soil Quality Metrics under Agricultural and Municipal Biosolid Applications," 2016 Manure and Soil Health Working Group Report. Soil Health Nexus.

Sedron Technologies. n.d. "Varcor System." Sedron Technologies, Sedro-Woolley, WA.

Sharara, M.A., M.Y. Owusu-Twum, T.M. Runge, and R. Larson. 2020. "Planning Methodology for Anaerobic Digestion Systems on Animal Production Facilities under Uncertainty," *Waste Management* 104(March):262–69.

Sharpley, A., N. Slaton, T. Tabler, K. VanDevender, M. Daniels, F. Jones, and T. Daniel. 2009. "Nutrient Analysis of Poultry Litter," Research and Extension Report FSA9529. University of Arkansas Division of Agriculture, Fayetteville, AR.

Shreve, B.R., P.A. Moore, T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. "Reduction of Phosphorus in Runoff from Field-Applied Poultry Litter Using Chemical Amendments," *Journal of Environmental Quality* 24(1):106–11.

Shurson, G. 2018. *Precision DDGS Nutrition: 4th edition*. Washington D.C.: U.S. Grains Council.

Sims, B. 2009. "Panda Ethanol Subsidiary Files for Bankruptsy Protection," *Ethanol Producer Magazine*, January 12, 2009.

Sims, J.T., and N.J. Luka-McCafferty. 2002. "On-Farm Evaluation of Aluminum Sulfate (Alum) as a Poultry Litter Amendment," *Journal of Environmental Quality* 31(6):2066–73.

Smith, D.W., S. Mukhtar, and R.R. Stowell. 2014. *Advanced Application Techniques-Making the Most of Your Manure Responsibly*, Texas A&M Agrilife Extension, College Station, TX.

Sneeringer, S. 2016. "Comparing Participation in Nutrient Trading by Livestock Operations to Crop Producers in the Chesapeake Bay Watershed," ERR-216. U.S. Department of Agriculture, Economic Research Service, September 2016.

Sneeringer, S., and N. Key. 2011. "Effects of Size-Based Environmental Regulations: Evidence of Regulatory Avoidance," *American Journal of Agricultural Economics* 93(4):1189–1211.

Sorensen, A. 2011. *Barriers and Solutions for Farmer Participation in the Ohio River Basin Water Quality Trading Program*, Technical Update 1023642. ERPI. American Farmland Trust, Washington, DC.

Sørensen, P., and J. Eriksen. 2009. "Effects of Slurry Acidification with Sulphuric Acid Combined with Aeration on the Turnover and Plant Availability of Nitrogen," *Agriculture, Ecosystems & Environment* 131(3):240–46.

Spiegal, S., P.J.A. Kleinman, D.M. Endale, R.B. Bryant, C. Dell, S. Goslee, R.J. Meinen, K.C. Flynn, J.M. Baker, D.M. Browning, G. McCarty, S. Bittman, J. Carter, M. Cavigelli, E. Duncan, P. Gowda, X. Li, G.E. Ponce-Campos, R. Cibin, M.L. Silveira, D.R. Smith, D.K. Arthur, Q. Yang, 2020. "Manuresheds: Advancing Nutrient Recycling in U.S. Agriculture," *Agricultural Systems* 182(February):102813–102813.

Sprick, M. 2017. *Comparison of Options for Biosolids Dewatering*, Presented at the Water Environment School 2017, Clackamas Community College, Oregon City, Oregon, March 28.

Stahlman, M., and L. McCann. 2012. "Technology Characteristics, Choice Architecture, and Farmer Knowledge: The Case of Phytase," *Agriculture and Human Values* 29(3):371–79.

Stevenson, W.H., P.E. Brown, L.W. Forman, W.G. Baker, J.L. Boatman, and B. Boatman. 1926. *The Economic Value of Farm Manure as a Fertilizer on Iowa Soils*, Bulletin number 236. Agricultural Experiment Station, Iowa State College of Agricultural and Mechanical Arts, Ames, IA.

Stingone, J., and S. Wing. 2011. "Poultry Litter Incineration as a Source of Energy: Reviewing the Potential for Impacts on Environmental Health and Justice," *New Solutions: A Journal of Environmental and Occupational Health Policy* 21(1):27–42.

Stubbs, M. 2020. *Agricultural Conservation: A Guide to Programs*, R40763, Congressional Research Service, Washington, DC.

Sun, Y., G. Niu, A.K. Koeser, G. Bi, V. Anderson, K. Jacobsen, R. Conneway, S. Verlinden, R. Stewart, and S.T. Lovell. 2015. "Impact of Biocontainers on Plant Performance and Container Decomposition in the Landscape," *HortTechnology* 25(1):63–70.

Sunding, D., and D. Zilberman. 2001. "The Agricultural Innovation Process: Research and Technology Adoption in a Changing Agricultural Sector," in *Handbook of Agricultural Economics*. Amsterdam, Netherlands:Elsevier.

Sustainable Phosphorus Alliance. 2021. "GIS-P." Sustainable Phosphorus Alliance, Tempe, AZ.

Sweeten, J.M., and B.W. Auvermann. 2008. *Composting Manure and Sludge*, L–2289, Texas Agricultural Extension Service, College Station, TX.

Swindal, M.G., G.W. Gillespie, and R.J. Welsh. 2010. "Community Digester Operations and Dairy Farmer Perspectives," *Agriculture and Human Values* 27(4):461–74.

Taiwo, A. and E. Ama Otoo. 2013. *Accelerating Decomposition Rate of Fresh Faecal Materials from a Farrow-to-Finish Swine Farm with Black Soldier Fly Larvae '(Hermetia Illucens)*, In 2013 ASABE Annual International Meeting. American Society of Agricultural and Biological Engineers, Kansas City, MO.

Tchobanoglous, G., F. Burton, and D. Stensel. 2003. *Wastewater Engineering: Treatment and Reuse: 4th Edition*. New York, NY: McGraw Hill.

Texas Pork Producers Association. n.d. "History of Pork," Texas Pork Producers Association, Lubbock, TX.

The Global Syngas Technologies Council. 2021. "Syngas Production" The Global Syngas Technologies Council, Arlington, VA.

The MBR Site. 2020. "O&M – MBR Fouling, Clogging and Cleaning,." The MBR Site, Fenny Stratford, Buckinghamshire, UK.

The Regional Greenhouse Gas Initiative. 2021. "Agricultural Methane," New York, NY.

Thompson, E., Q. Wang, and M. Li. 2013. "Anaerobic Digester Systems (ADS) for Multiple Dairy Farms: A GIS Analysis for Optimal Site Selection," *Energy Policy* 61(October):114–24.

Thompson, P., telephone interview and email exchange with the author, February, 2021.

Tinbergen, J. 1952. *On the Theory of Economic Policy*: 2nd Edition, Amsterdam, Netherlands: North-Holland Publishing Company.

Tozer, P.R., and J.R. Stokes. 2001. "A Multi-Objective Programming Approach to Feed Ration Balancing and Nutrient Management," *Agricultural Systems* 67(3):201–15.

U.S. Department of Agriculture. 2018. "Broiler Industry Highlights," 2011 Agricultural Resource Management Survey, U.S. Department of Agriculture, Washington, DC.

U.S. Department of Agriculture, Rural Development. 2019. "Value-Added Producer Grants: Anaerobic Digesters," U. S. Department of Agriculture, Rural Development, Washington, D.C.

U.S. Department of Agriculture. 2019. "USDA Has More Than $400 Million Still Available for Renewable Energy System and Energy Efficiency Loan Guarantees," U.S. Department of Agriculture, Washington, DC.

U.S. Department of Agriculture, Economic Research Service. 2020. "Poultry Sector at a Glance," U.S. Department of Agriculture, Economic Research Service, Washington, DC.

U.S. Department of Agriculture, Farm Service Agency. 2019. "Your Guide to FSA Farm Loans," U.S. Department of Agriculture, Farm Service Agency, Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service. 2021. "CIG Success Spotlight," U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service. n.d. "Conservation Practices," U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, DC. (accessed February 25, 2021).

U.S. Department of Agriculture, Rural Development. 2019. "Value-Added Producer Grants: Anaerobic Digesters," U. S. Department of Agriculture, Rural Development, Washington, D.C.

U.S. Department of Agriculture, Rural Development. 2020. "Rural Energy for America Program (REAP) Renewable Energy & Energy Efficiency," U.S. Department of Agriculture, Rural Development, Washington, DC.

U.S. Department of Energy. 2021. "Alternative Fuels Data Center: Renewable Fuel Standard," U.S. Department of Energy, Washington, DC.

U.S. Energy Information Administration. 2022. "EIA Forecasts Natural Gas Prices to Remain Near $4/ MMBtu in 2022, Slightly Lower in 2023," U.S. Energy Information Administration, Washington, DC. (accessed on January 21, 2022).

U.S. Environmental Protection Agency. 1995. *Guide Manual on NPDES Regulations for Concentrated Animal Feeding Operations*, EPA 833-B-95-001, U.S. Environmental Protection Agency, December 1995.

U.S. Environmental Protection Agency. 2000a. *Biosolids Technology Fact Sheet: Belt Filter Press*, EPA 832-F-00-057, U.S. Environmental Protection Agency, September 2000.

U.S. Environmental Protection Agency. 2000b. *Biosolids Technology Fact Sheet: Recessed-Plate Filter Press*, EPA 832-F-00-058, U.S. Environmental Protection Agency, September 2000.

U.S. Environmental Protection Agency. 2000c. *Centrifuge Thickening and Dewatering*, EPA 832-F-00-053, U.S. Environmental Protection Agency, September 2000.

U.S. Environmental Protection Agency. 2007. *Waste Water Management Fact Sheet: Membrane Bioreactor*. U.S. Environmental Protection Agency, September 2007.

U.S. Environmental Protection Agency. 2021a. "Federal Income Tax Credits and Other Incentives for Energy Efficiency." U.S. Environmental Protection Agency, Washington, DC.

U.S. Environmental Protection Agency. 2021b. "RIN Trades and Price Information, Other Policies and Guidance," U.S. Environmental Protection Agency, Washington, DC.

U.S. Environmental Protection Agency. 2021c. "Water Quality Trading−National Pollutant Discharge Elimination System (NPDES)," U.S. Environmental Protection Agency, Washington, DC.

U.S. Environmental Protection Agency. 2021d. "Livestock Anaerobic Digester Database," U.S. Environmental Protection Agency, Washington, DC.

Utley, K., telephone interview with author, January 28, 2021.

VDL Adgrtotech. n.d. "Manure Drying," VDL Agrotech, Eindhoven, Netherlands.

Waldrip, H.M., P.H. Pagliari, and Z. He. "Animal Manure: Production, Characteristics, Environmental Concerns, and Management." *ASA Special Publications*, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, WI.

Wander, M. 2019. "Managing Manure Fertilizers in Organic Systems," eOrganic.org November 8, 2019.

Wang, C., H. Lu, D. Dong, H. Deng, P.J. Strong, H. Wang, and W. Wu. 2013. "Insight into the Effects of Biochar on Manure Composting: Evidence Supporting the Relationship between N2O Emission and Denitrifying Community," *Environmental Science & Technology* 47(13):7341–49.

Wang, Q., E. Thompson, A. Tweedy, M.L. O'Leary, and W.W. Crossman. 2021. "Potentials and Obstacles for Community Anaerobic Digesters in the United States: Evidence from a Case Study in Vermont," *Renewable and Sustainable Energy Reviews* 137(March):110434.

Wang, Q., E. Thompson, L. Valchuis, and R. Parsons. 2017. "Energy Outputs and Financial Returns of On-Farm Biodigester Systems in the United States: A Case Study in Vermont," *International Journal of Sustainable and Green Energy* 6(2):10.

Wang, Y., W. Guo, H. Yen, S. Ho, Y. Lo, C. Cheng, N. Ren, and J. Chang. 2015. "Cultivation of Chlorella Vulgaris JSC-6 with Swine Wastewater for Simultaneous Nutrient/COD Removal and Carbohydrate Production," *Bioresource Technology* 198(December):619–25.

Ward, M. 2016. "Turkey Growers Create Compost Co-Op," Missouri Ruralist. June 28, 2016.

Warren, J.G., C.J. Penn, J.M. McGrath, and K. Sistani. 2008. "The Impact of Alum Addition on Organic P Transformations in Poultry Litter and Litter-Amended Soil," *Journal of Environmental Quality* 37(2):469–76.

Washington State University. 2020. "The Mobile Struvite Project," *Livestock Nutrient Management Site* (blog), Washington State University, Pullman, WA.

Webb, J., B. Pain, S. Bittman, and J. Morgan. 2010. "The Impacts of Manure Application Methods on Emissions of Ammonia, Nitrous Oxide and on Crop Response—A Review," in special section Harvested Perennial Grasslands: Ecological Models for Farming's Perennial Future, *Agriculture, Ecosystems & Environment*, 137(1):39–46.

Westerman, P.W., K.E. Bowers, and K.D. Zering. 2010. "Phosphorus Recovery from Covered Digester Effluent with a Continuous-Flow Struvite Crystallizer," *Applied Engineering in Agriculture* 26(1):153–61.

White, M.J., C. Santhi, N. Kannan, J.G. Arnold, D. Harmel, L. Norfleet, P. Allen, M. DiLuzio, X. Wang, J. Atwood, E. Haney, M. Vaughn Johnson, 2014. "Nutrient Delivery from the Mississippi River to the Gulf of Mexico and Effects of Cropland Conservation," *Journal of Soil and Water Conservation* 69(1):26–40.

White, M.J., D.E. Storm, P.R. Busteed, S.H. Stoodley, and S.J. Phillips. 2009. "Evaluating Nonpoint Source Critical Source Area Contributions at the Watershed Scale," *Journal of Environmental Quality* 38(4):1654–63.

Williams, R., telephone interview with author, August 28, 2020.

Whitt, C., J.E. Todd, J.M. MacDonald. 2020. *America's Diverse Family Farms: 2020 Edition*, EIB-220, U.S. Department of Agriculture, Economic Research Service, December 2020.

Yorgey, G., C. Kruger, K. Steward, C. Frear, and N. Mena. 2011. *Anaerobic Co-Digestion on Dairies in Washington State*, FS040E, Washington State University Extension, Pullman, WA.

Yue, C., C.R. Hall, B.K. Behe, B.L. Campbell, J.H. Dennis, and R.G. Lopez. 2010. "Are Consumers Willing to Pay More for Biodegradable Containers than for Plastic Ones? Evidence from Hypothetical Conjoint Analysis and Non-Hypothetical Experimental Auctions," in 2010 *AAEA Annual Meeting*, Denver, CO.

Zemo, K.H., and M. Termansen. 2018. "Farmers' Willingness to Participate in Collective Biogas Investment: A Discrete Choice Experiment Study," *Resource and Energy Economics* 52(May):87–101.

Zhang, X., C. Wang, and Y. Chen. 2019. "Properties of Selected Biodegradable Seedling Plug-Trays," *Scientia Horticulturae* 249(April):177–84.

Zhang, Y., M.A. White, and L.M. Colosi. 2013. "Environmental and Economic Assessment of Integrated Systems for Dairy Manure Treatment Coupled with Algae Bioenergy Production," *Bioresource Technology* 130(February):486–94.

Appendix A: Data Availability Challenges

Two data availability challenges exist when estimating manure excretion quantity by location.

First, the number of counties with nondisclosed data has increased over time and created challenges for county-based estimates. This is particularly prevalent in counties that may have one or two large animal feeding operations. The data are not disclosed for the county but are included in regional, State, or national totals. For example, the number of nondisclosed counties for hogs increased from 398 in 1997 to 520 in 2017. For dairy, the number of nondisclosed counties rose from 482 in 1997 to 704 in 2017.

A second data concern is the age of nutrient excretion estimates. The most recently published report on manure characteristics is Pagliari et al. (2020), Animal Manure Production and Utilization. Table 1 of this publication says the data source for the calculations throughout the chapter—with modifications for horses and dairy—trace back to ASAE D384.2 Manure Production and Characteristics (2005), which was reaffirmed but not revised in 2010.

It is uncertain whether the ASAE D384.2 (2005) estimates of nutrients excreted accurately reflect modern animal production. Significant changes have occurred in feeding and management that affect manure excretion. D384.2 references National Research Council Nutrient Requirements of [species] monographs for sources used to estimate animal performance. Table A.1 shows the edition used for ASAE D384.2 and the latest edition of those recommendations. Swine, beef cattle, and horses have updated recommendations not included in ASAE D384.2.

Table A.1

Year of publication of NRC[1] nutrient recommendation for various animal species

Species	NRC nutrient recommendations	
	Most recent ASABE Standard D384.2[2]	Most recent NRC edition
Dairy	2001	2001
Swine	1998	2012
Beef cattle	1996	2016
Laying hens	1994	1994
Horses	1989	2007

1NRC = National Research Council.

[2]ASABE Standard D384.2, Manure Production and Characteristics, is published by the American Society of Agricultural and Biological Engineers.

Source: USDA, Economic Research Service using information from American Society of Biological and Agricultural Engineers, "Manure Production and Characteristics."

NCR *Nutrient Requirements for Swine* (2012) notes the correlation between increased feed efficiency and decreased nutrient excretion. It specifically points to the following elements that increase feed efficiency and reduce nutrient excretion: genetic improvements, housing environmental control, diet formulation, the use of metabolism modifiers such as amino acid supplements and phytase, feed processing, and feed delivery (NCR, page 198). Each of these elements has changed significantly in the past several decades—particularly for confined animal production of hogs, poultry, and dairy. This indicates manure generation estimates may be overstated (see McGrath et al., 2005 for impact of ration on broiler litter). Updated data on manure output, given improved animal production systems, would provide better estimates for the important work of identifying nutrient sources and sinks.

Appendix B: Manure Nitrogen-to-Phosphorus Ratios

The nitrogen and phosphorus levels in manure sourced from various animals and applied in various methods impact manure's value to crop producers. Table B.1 presents calculated nitrogen-to-phosphorus ratios for several types of manures. These can be compared to crop nitrogen and phosphorus needs (table B.2) to draw quick inferences to the value of a manure source and the potential impact of management decisions.

Table B.1
Nitrogen-to-phosphorus ratios for different sources of manure and different manure application methods

	Injected			Surface applied		
Species	Lagoon	Pit	Solid manure	Lagoon	Pit	Solid manure
Beef cows		0.8	1.2		0.7	1.0
Beef fattening	0.3			0.2		
Beef feeder		0.9	1.4		0.8	1.2
Beef finishing		1.0	1.0		0.9	0.8
Chicken - broilers	1.0	0.9	0.5	0.7	0.8	0.5
Chicken - layers		0.8	0.4		0.6	0.4
Chicken - pullets		1.0	0.8		0.9	0.7
Dairy calf		1.1	1.9		1.0	1.7
Dairy cow	1.0	1.2	1.9	0.8	1.1	1.7
Dairy heifer		1.3	1.9		1.2	1.7
Dairy herd	1.0	1.2	1.3	0.8	1.1	1.2
Ducks		0.9	0.5		0.8	0.4
Veal		1.0	2.2		0.7	1.7
Swine breeding - gestation	3.0	0.7	0.9	2.1	0.5	0.7
Swine farrow-feeder		0.8			0.6	
Swine farrow-finish	3.0	0.9	1.2	2.1	0.7	1.0
Swine farrowing	3.0	0.9	1.4	2.1	0.7	1.2
Swine feeder pig			1.0			0.8
Swine grow-finish	3.0	0.9	1.2	2.1	0.7	1.0
Swine nursery		1.0	1.1		0.7	0.9
Turkeys - hen		1.0	0.5		0.8	0.4
Turkeys - tom		0.8	0.5		0.7	0.4

Source: USDA, Economic Research Service using data obtained from Manure Characteristics, published by Midwest Plan Service, report MWPS-18, to calculate the nitrogen-to-phosphorus ratios.

Table B.2

Nitrogen-to-phosphorus removal ratio for major crops in the United States

Crop	Nitrogen-to-phosphorus ratio
Corn	1.9
Soybeans	[a]
Corn-soy rotation	1.2
Wheat	2.6
Cotton	2.3
Barley	2.5
Oats	2.8
Sorghum	1.7
Peanuts	[a]

[a]Soybeans and peanuts are legumes not needing nitrogen fertilizers, so their fertilizer nitrogen-to-phosphorus removal ratio is not relevant.

Source: USDA, Economic Research Service using data obtained from Manure Characteristics, published by Midwest Plan Service, report MWPS-18, to calculate the nitrogen-to-phosphorus ratios.

Appendix C: Liquid Digestate Characteristics

Processing manure through anaerobic digestion produces a digestate that is used in other processes, including land application as a source of crop nutrients. Table C.1 reports the digestate characteristics discovered from various research projects.

Table C.1

Characteristics of liquid digestates of different origins

Ingestate	Digestion process	Total-N (Nt)	NH_4-N	Total-P	Total-K	Source of data
Swine manure	mesophilic	2.93 (g/L)	2.23 (g/L)	0.93 (g/L)	1.37 (g/L)	*Loria et al., 2007*
Liquid cattle slurry	mesophilic	4.27 (%DM)	52.9 (% Nt)	0.66 (% DM)	4.71 (% DM)	*Moller et al., 2008*
Energy crops, cow manure slurry and agro-industrial waste	thermophilic	105 (%TS)	2.499 (g/L)	10.92 (% TS)	-	*Pognani et al., 2009*
Energy crops, cow manure slurry, agro-industrial waste, and OFMSW	thermophilic	110 (% TS)	2.427 (g/L)	11.79 (%TS)	-	*Pognani et al., 2009*
Cow manure, plant residues, and offal	mesophilic and thermophilic	0.2013 (% by mass, fresh matter)	0.157 (% by mass, fresh matter)	274.5 (% by mass, fresh matter)	736.45 (% by mass, fresh matter)	*Makadi et al., 2008b*
Clover/grass or pea straw or silage maize and clover/grass silage (mean)	mesophilic	0.253 (% by mass, fresh matter)	0.176 (% by mass, fresh matter)	0.62 (% DM)	18.5 (% DM)	*Stinner et al., 2008*

Notes: N = nitrogen; NH_4-N = nitrogen in ammonium form; P = phosphorus; K = potassium; DM = dry matter; TS = total solids; OFMSW = organic fraction of municipal solid waste.

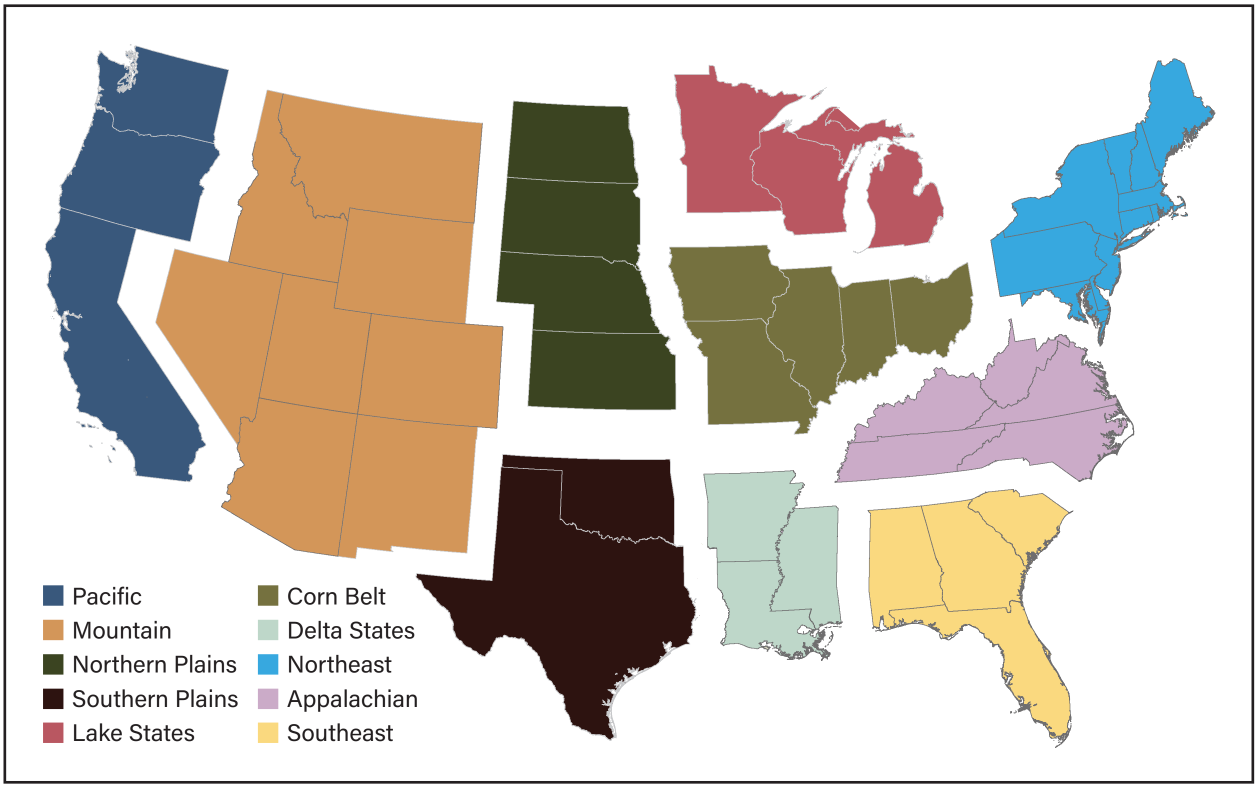
Unit definitions: L = liter; g = grams; kg = kilograms.

Source: USDA, Economic Research Service using data obtained from "Digestate: a new nutrient source–review." Chapter in Biogas, ECDC-TCDC Services, Denmark, pages 295–312.

Appendix D: U.S. Department of Agriculture, Farm Production Regions

Figure D.1

U.S. Department of Agriculture, farm production regions



Source: USDA, Economic Research Service, Agricultural Information Bulletin Number 760.