MANURE TREATMENT TECHNOLOGIES

Recommendations from the Manure Treatment Technologies Expert Panel to the Chesapeake Bay Program's Water Quality Goal Implementation Team to define Manure Treatment Technologies as a Best Management Practice

ABSTRACT

Treatment technologies are used on livestock farms for three main purposes: to stabilize manure organic matter, to make manure easier to handle, and to generate on-farm energy. While performing these functions, manure treatment technologies profoundly affect the manner in which nutrients flow through the farm and environment. This report focuses on six broad categories of treatment technologies: Thermochemical Processing, Composting, Anaerobic Digestion, Settling, Mechanical Solid Liquid Separation, and Wet Chemical Treatments. The ability to reduce nitrogen by volatilization and to separate both nitrogen and phosphorous to a stream that is likely to be utilized off-farm is quantified for each technology. Transformation of nutrients to more plant-available forms is also discussed for each technology.

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Approved by the Agriculture Workgroup: TBD
Approved by the Watershed Technical Workgroup: TBD
Approved by the Water Quality GIT: TBD

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Executive Summary

The Manure Treatment Technologies Expert Panel convened in December 2014 and over subsequent months worked to evaluate the nutrient reduction benefits associated with the various categories of manure treatment technologies described in this report, specifically:

1. Thermochemical Conversion
2. Composting
3. Anaerobic Digestion
4. Settling
5. Mechanical Solid-Liquid Separation
6. Wet Chemical Treatment

The panel defined individual technologies within each category. Using data available in the literature, the panel determined how each defined technology affects and transforms nitrogen and phosphorus in the manure stream. The panel also chose to describe how the technology affects manure organic matter in most cases.

The panel chose to approach each manure treatment technology as a Black Box (Figure ES.1). As shown in Figure ES.1, nutrients are not typically ***removed*** by manure treatment technologies. Rather treatment technologies ***transfer*** manure nutrients to three possible flow paths (arrows leaving the box in Figure ES.1). Nutrients (both nitrogen and phosphorus) often remain in treatment flow paths to be utilized on-farm via application to crops and pasture. Nitrogen can be transferred (volatilized) to the atmosphere (dashed arrow in in Figure ES.1) as either nitrogen gas (N_2), ammonia (NH_3), or various oxides of nitrogen (NO_x). Nutrients (both nitrogen and phosphorus) can be separated from the main manure flow path and transferred to another flow path, which is more likely to be utilized off-farm.

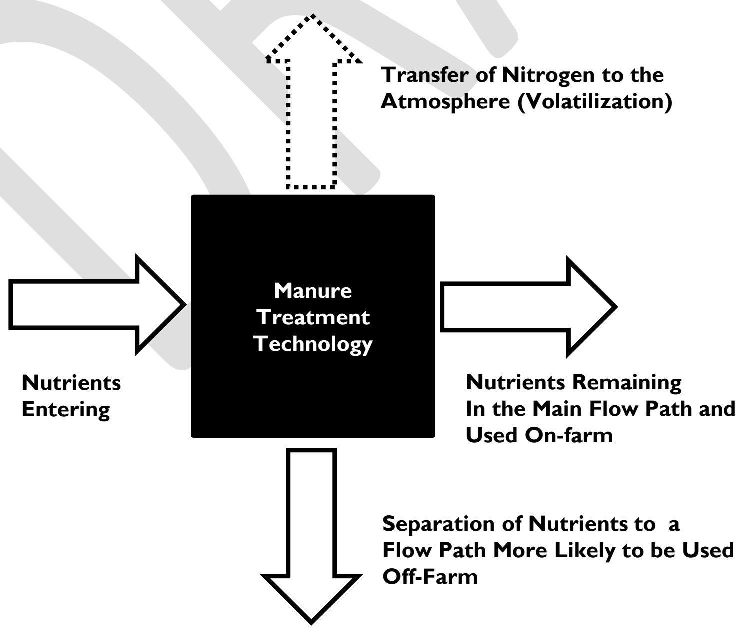

Figure ES.1. Manure Treatment Technologies as a "Black Box"

The panel chose Mass Transfer Efficiency as the method to express how manure treatment technologies alter nutrient flows. In terms of the black box given in Figure ES.1, mass transfer efficiency is calculated as:

$$\textbf{Mass Transfer Efficiency} = \frac{\text{(Mass of Nutrients in a Flow Path Leaving the Box)}}{\text{(Mass of Nutrients Entering the Box)}} \times 100 \qquad \text{ES.1}$$

Three specific transfer efficiencies were calculated for each technology: Nitrogen Volatilization Efficiency (NVE), Nitrogen Separation Efficiency (NSE), and Phosphorus Separation Efficiency (PSE). Equations used to calculate these efficiencies are given in ES.2, ES.3, and ES.4.

$$\textbf{NVE} = \frac{\text{(Mass of Nitrogen Transferred to Atmosphere)}}{\text{(Mass of Nitrogen Entering the Treatment Technology)}} \times 100 \qquad \text{ES.2}$$

$$\textbf{NSE} = \frac{\text{(Mass of Nitrogen Separated from Main Flow Path)}}{\text{(Mass of Nitrogen Entering the Treatment Technology)}} \times 100 \qquad \text{ES.3}$$

$$\textbf{PSE} = \frac{\text{(Mass of Phosphorus Separated from Main Flow Path)}}{\text{(Mass of Phosphorus Entering the Treatment Technology)}} \times 100 \qquad \text{ES.4}$$

Mass Transfer Efficiency Recommendations

Two levels of mass transfer efficiencies are recommended by the panel for use by the Chesapeake Bay Program:

1. **Default Transfer Efficiency** (Level 1) to be used when the only things known about a treatment system are the manure and treatment technology type.
2. **Defined Transfer Efficiency** (Level 2) to be used when the manure type is known and pertinent operating conditions of the treatment technology are known.

A third level of mass transfer may be used by the Chesapeake Bay Program if monitoring data exists for the treatment system in question:

3. **Data Driven Transfer Efficiency** (Level 3) to be used when actual monitoring data for a particular farm is available.

While the panel provides values about the NVE, NSE and PSE wherever possible, only technologies that remove nutrients from the primary manure stream can receive a reduction efficiency in the Phase 6.0 Chesapeake Bay Watershed Model. Only those technologies with a NVE value (i.e., volatilization) remove nitrogen from the manure via the treatment technology. “Removal” in this case means that the nitrogen is no longer present in the treated manure that is available for field application or transport according to model procedures that occur post-treatment. The following manure treatment practices may be reported to the National Environmental Information Exchange Network (NEIEN) for credit in a Phase 6 progress scenario or ~~reported to the CBPO for credit~~used in a planning scenario:

Table ES.1. Manure Treatment BMPs eligible for crediting in the Phase 6.0 Watershed Model and associated TN reduction

Practice Number	Practice Category	Technology Specifications*	TN Removal (%)
MTT1†	Thermochemical	Slow Pyrolysis	25
MTT2	Thermochemical	Fast Pyrolysis**	75
MTT3	Thermochemical	Gasification-Low Heat	25
MTT4	Thermochemical	Gasification-High Heat**	85
MTT5	Thermochemical	Combustion	85
MTT6	Thermochemical	Combustion-High Heat**	95
MTT7†	Composting	In-Vessel and Rotating Bin- Standard	10
MTT8	Composting	In-Vessel and Rotating Bin- C:N>100**	11
MTT9	Composting	In-Vessel and Rotating Bin- C:N<100**	13
MTT10	Composting	Forced Aeration- Standard	25
MTT11	Composting	Forced Aeration- C:N>100**	28
MTT12	Composting	Forced Aeration- C:N<100**	32
MTT13	Composting	Turned Pile and Windrow- Standard	25
MTT14	Composting	Turned Pile and Windrow- C:N>100**	28
MTT15	Composting	Turned Pile and Windrow- C:N<100**	32
MTT16	Composting	Static Pile and Windrow- Standard	26
MTT17	Composting	Static Pile and Windrow- C:N>100**	29
MTT18	Composting	Static Pile and Windrow- C:N<100**	33
MTT19	Directly Monitored		Monitored

* Definitions for specific thermochemical and composting technologies can be found in the report in Sections 4 and 5, respectively.
**Information about process factors, as described in Section 4, pages 29 - 32, and Section 5, pages 43-48, is needed to report these BMPs
†MTT1 represents the default practice Thermochemical treatment systems, and MTT7 represents the default for composting treatment systems.

[Editor's note that will be removed in final version: The values in Table ES.1 and Table A.2 in Appendix A will be revised at a future date to reflect a future decision from the Modeling Workgroup on how to simulate and account for emissions and redeposition of reactive nitrogen from BMPs within the watershed, including but not limited to the BMPs recommended by this panel.]

Although manure treatment technologies without a NVE value do not remove nutrients from the overall manure stream that is land applied or transported, they create numerous environmental benefits. By stabilizing and reducing organic matter, they reduce nuisance conditions and make plant nutrients more marketable for off-farm use. Manure treatment technologies also transform nutrients, which, in most cases, enhance plant nutrient uptake.

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List of common acronyms used in this document

AFO	Animal Feeding Operation
AgWG	Agriculture Workgroup
BMP	Best Management Practice
CAFO	Concentrated Animal Feeding Operation
CBP	Chesapeake Bay Program
CBPO	Chesapeake Bay Program Office
CBWM	Chesapeake Bay Watershed Model
EPA	U.S. Environmental Protection Agency
MTT	Manure Treatment Technology
NEIEN	National Environmental Information Exchange Network
NSE	Nitrogen Separation Efficiency
NVE	Nitrogen Volatilization Efficiency
PSE	Phosphorus Separation Efficiency
TCC	Thermochemical Conversion
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Sediment
USDA	U.S. Department of Agriculture
USDA NRCS	U.S. Department of Agriculture, Natural Resources Conservation Service
VS	Volatile Solids
WQGIT	Water Quality Goal Implementation Team
WTWG	Watershed Technical Workgroup

1. Background: Charge and Membership of the Expert Panel

In September 2013 the Chesapeake Bay Program's Agriculture Workgroup (AgWG) approved the membership and formation of a Manure Treatment Technology subgroup that developed a report to detail the Charge and Scope of Work for an eventual expert panel that would evaluate the water quality benefits associated with the technologies in their charge. The subgroup's report was approved by the AgWG in June 2014 and directed the expert panel to evaluate the following technologies as new BMPs for the Chesapeake Bay Program (CBP) partnership's modeling tools:

- Microbial digestion
    - Aerobic
    - Anaerobic
- Thermochemical
    - Pyrolysis
    - Gasification
    - Combustion
    - Torrefaction
- Chemical treatments – dry manure
- Chemical treatments – wet manure
- Solid-liquid separation
- Composting

The subgroup considered a number of other treatment technologies – such as biological nutrient removal, pelletizing, enzymatic digestion, and baled poultry litter – but determined those technologies can either be adequately captured through the existing "manure transport" BMP (pelletizing and baled poultry litter) or did not have enough available data to review at this time.

Table B.1 – Membership of the Manure Treatment Technologies BMP Expert Panel	
Panelist	**Affiliation**
Keri Cantrell	KBC Consulting (formerly with USDA-ARS)
John Chastain	Clemson University
Doug Hamilton (Chair)	Oklahoma State University
Andrea Ludwig	University of Tennessee
Robert Meinen	Penn State University
Jactone Ogejo	Virginia Tech
Jeff Porter	USDA-NRCS, Eastern National Technology Support Center
Panel support:	
Jeremy Hanson (Coord.)	Virginia Tech/CBPO
Brian Benham	Virginia Tech (Cooperative Agreement Project Director)
Chris Brosch	Delaware Dept. of Agriculture (WTWG rep)
Mark Dubin	University of Maryland/CBP (AgWG Coord.)
Ashley Toy	EPA Region 3 (Regulatory Support)
David Wood	CRC/CBP (CBP modeling team rep)

Virginia Tech, under its cooperative agreement with EPA to facilitate BMP expert panels, released a Request for Proposals in September 2014 to solicit the formation of a panel to fulfill the Charge approved by the AgWG. The proposal submitted by Doug Hamilton (Oklahoma State) was selected and presented to the AgWG and CBP partnership for comment. The panel membership, as approved by the AgWG in November 2014, is summarized in Table B.1.

The panel convened for its first meeting and hosted a public stakeholder forum[1] on December 15, 2014. Throughout its deliberations, the panel adhered to the procedures and expectations described in the Water Quality Goal Implementation Team's *Protocol for the Development, Review, and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls in the Chesapeake Bay Watershed Model*, or BMP Protocol.[2]

The panel would like to acknowledge Matt Johnston (University of Maryland, CBPO), Jeff Sweeney (EPA, CBPO), members of the Agriculture workgroup and others whose continued interest and input provided valuable contributions to the development of this report.

[1] http://www.chesapeakebay.net/calendar/event/22245/
[2] http://www.chesapeakebay.net/publications/title/bmp_review_protocol

2. Background: Livestock Manure Treatment in the Bay Watershed

Manure from animal agriculture is the largest source of phosphorus (P) loads to the Chesapeake Bay and the second largest source of nitrogen (N). Traditionally, the manure from livestock and poultry has been a valuable resource for farmers as a cost-effective fertilizer. When used appropriately, manure adds nutrients and organic matter that improves soil quality. However, manure's ratio of P to N is often higher than a crop's agronomic need, so application of manure at agronomic N rates frequently contributes to excess P in the soil. Manure is also a bulky material that is costly and energy intensive to transport long distances to areas where it is needed. ~~Excess nutrients in some areas of watershed make nutrients in the soil more susceptible to runoff.~~Nutrients are often applied at excessive rates in areas of the watershed where excess manure exist. Resulting excess nutrient levels in soils in these areas increase susceptibility to nutrient loss via runoff.

The need to rebalance the use of nutrients to protect water quality has generated interest and investment in manure treatment technologies and alternate uses of manure. Additionally, revisions to P management regulations (e.g., Maryland) further increase the need for such manure technologies. Some technologies have been in use for decades (e.g., anaerobic digesters) while others are much newer and still in the pilot or research stage.

How Nutrient Loads from Livestock Manure are Currently Simulated in the Chesapeake Bay Watershed Model (v.5.3.2)

The Chesapeake Bay Watershed Model (CBWM) is one part of a larger suite of tools used by Chesapeake Bay Program partners, as illustrated in Figure B.1. The Watershed Model combines all BMP, land use and nutrient input data to estimate delivered loads of N, P and sediment to the Chesapeake Bay. The Estuarine Model then uses these delivered loads to assess attainment of water quality standards. The current version of the CBWM (Phase 5.3.2) is calibrated to water quality monitoring data over the period of 1985 to 2005.

Scenario Builder

Scenario Builder is a database management tool that combines a wide array of inputs for a given year and processes them into a single, comprehensive scenario for the CBWM to run, as illustrated in Figure 1 above. Scenario Builder is the tool where manure and nutrient inputs are combined with BMP implementation data reported by the states through the National Environmental Information Exchange Network (NEIEN).

How Scenario Builder simulates agricultural nutrient inputs from animal manures

The current version of Scenario Builder estimates nutrient applications to crops on a monthly basis. Monthly nutrient needs for each crop in each county are estimated based upon acres of crops reported by the USDA National Agricultural Statistics Service (NASS) Census of Agriculture (Ag Census) and yield and application rate/timing data provided by the Ag Census, literature sources and state agricultural agencies. The monthly nutrient need of each crop can be met by organic nutrients (manure and biosolids) and/or by inorganic nutrients (fertilizer).

Nutrients are spread in a stepwise fashion in the current version of Scenario Builder. First, a few high-need commodity crops receive inorganic nutrients to mimic common nutrient

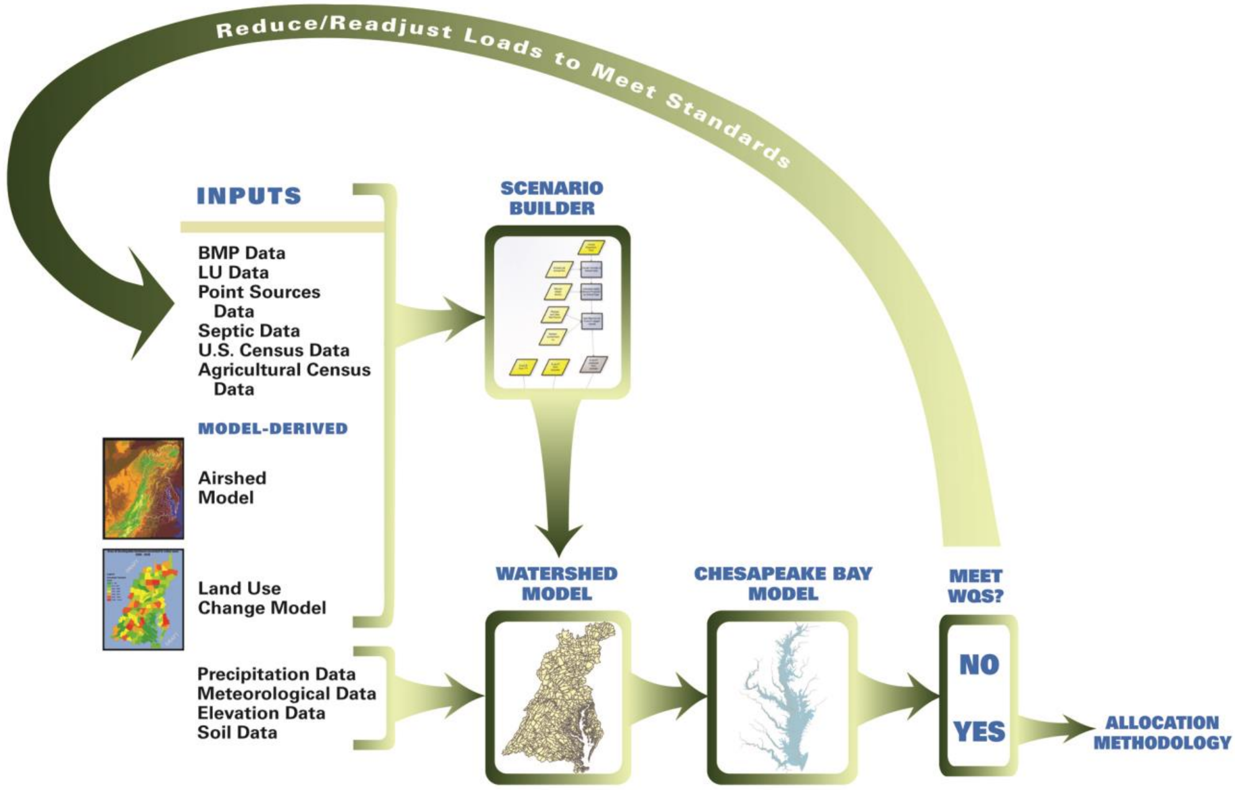

Figure B.1 - Chesapeake Bay Program partnership modeling tools

application routines. Next, a portion of organic nutrients is deposited directly on pasture to reflect manure deposition that occurs outside of the barnyard. Third, organic nutrients deposited within the barnyard are spread to meet the nutrient needs for crops which typicallyreceive organic nutrients. Finally, inorganic fertilizer is spread to supplement any remaining crop nutrient need. Occasionally, there are more manure nutrients available in a county than Scenario Builder estimates crops should receive. When this occurs, all remaining manure is spread on specific crops in an order defined by each state. The next version of Scenario Builder may simulate manure generation and nutrient application in slightly different ways based on feedback and decisions by the CBP partnership. For the purposes of this panel, the overall process is expected to remain similar enough that the panel's recommendations can reasonably be incorporated into the next version of the CBP modeling tools.

Overview on how manure is simulated in CBP partnership modeling tools

This section briefly summarizes how manure is simulated in the modeling tools, and the next chapter describes how the panel approached treatment practices as related to the modeling tools. Appendix A provides additional details on how the BMPs can be reported through NEIEN and combined with other data (manure, nutrients, BMPs, etc.) in Scenario Builder.

Nutrients associated with manure go through five steps in the modeling tools. The steps outlined below are shown conceptually in Figure B.2.

1. Manure is produced/excreted.
2. Manure is placed in storage.
3. Nutrients may be volatilized.
4. Nutrients may be lost via manure storage and transport activities.
5. Manure (and associated nutrients) are applied to crops and/or pasture.

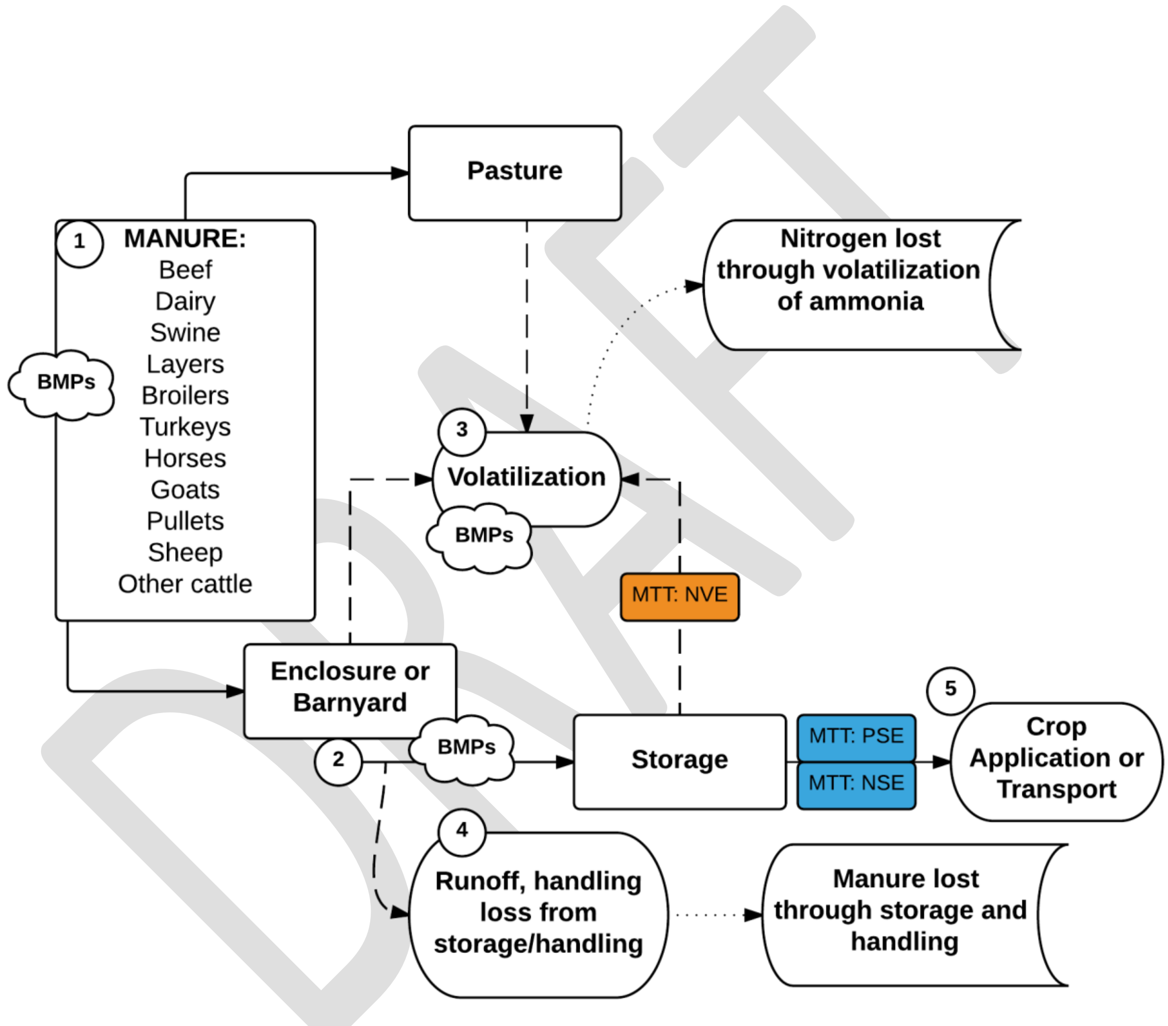

Figure B.2 - Conceptual Diagram of Manure Nutrients in the Phase 5.3.2 Watershed Model.

The panel was asked to determine "how much, on a percentage basis, total nitrogen (TN) or total phosphorus (TP) is lost or reduced as a result of the treatment technology or process?" If the technology only transforms N or P constituents, then the panel could also consider a corollary question, "how much of each constituent is transformed into a different constituent as a result of the treatment?" These two questions were essential for the panel to consider due to the way the modeling tools calculate the nutrient loads associated with manure are simulated in the CBP modeling tools, Figure B.2.

For modeling purposes, manure treatment technology simulation is a function of technology type, and the timing of when a given technology is applied to the manure. Manure treatment technology BMPs treat manure before it is land applied, specifically anytime during or after Step 2 and before Step 5 in Figure B.2 above. The orange MTT:NVE box in Figure B.2 illutrates the nitrogen that is extracted by certain treatment technologies (e.g., thermochemical or composting) from the primary manure stream that is subsequently available for land application or transport. The total overall nutrients remaining in that primary manure stream are not changed as a result of the PSE or NSE values since those nutrients still remain to be land applied or transported according to model procedures. Other assumptions and procedures in the modeling tools (e.g., field application, runoff, losses from storage/handling) are outside the scope of this Manure Treatment Technologies expert panel report and will apply to treated manure streams the same as untreated manure streams since the overall nutrients are part of the same overall "bucket" of manure nutrients at the county scale in the modeling tools.

Section 3 provides more information about how the panel approached how to conceptualize and quantify the benefits of manure treatment technologies in the context of the CBP partnership modeling tools.

References

Devereux, O. 2013. *Manure-Receiving Land Uses Load Estimation Methodology*. Accessed October 2014 from http://casttool.org/Documentation.aspx

Documentation for Scenario Builder, Version 2.4. Revised January 2013. Available online at http://www.chesapeakebay.net/publications/title/documentation_for_scenario_builder

Kellogg, R.L., Lander, C.H., Moffitt, D.C., & N. Gollehan, 2000. Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: spatial and temporal trends in the United States. NRCS and ERS GSA Publ. No. nps00-0579. Washington, D.C.

Schoenian, S. Sheep 201. Maryland Cooperative Extension. Accessed by CBPO staff and cited in Scenario Builder documentation, October, 2008, from http://www.sheep101.info/201/

3. Treatment Technologies in Manure Handling Systems

This panel was charged with developing definitions, determining loading effectiveness estimates, and defining nutrient transformation pathways for selected manure treatment technologies. The panel chose to concentrate on six broad categories of manure treatment technologies based on this charge, the likelihood that a given technology will be used in the Chesapeake Bay Watershed, and the availability of farm-scale performance data in the refereed literature.

The six technology categories the panel chose to examine were:

1. Thermochemical Conversion
2. Composting
3. Anaerobic Digestion
4. Settling
5. Mechanical Solid-Liquid Separation
6. Wet Chemical Treatment

The panel defined individual technologies within each broad category. Using data available in the literature, the panel determined how each defined technology affects and transforms N and P in a given manure stream. The panel also chose to describe how the technology affects manure organic matter in most cases.

Treatment is a Component of the Manure Handling System

Livestock farms use *systems* for handling manure. A system is as a set of interdependent components working together to accomplish a task. The general task of manure handling systems is to move manure (the feces and urine excreted by livestock) from animal housing to a place where it can be useful -- or at least less harmful -- to the environment. The system's components are interdependent because you cannot change one part of the system without affecting all of the other parts (Hamilton, 2011a).

Figure TT1 is a schematic representation of a manure handling system. The boxes are the various components of the system: manure is produced by animals, collected in a barn, transferred from place to place, utilized by crops, etc. The arrows in Figure TT.1 represent flow of material from one component to another. Two of the arrows have only one head, meaning manure flows generally from production to utilization. The three arrows into and out of the transfer component have two heads. This means that manure can travel in both directions between storage, treatment, and collection components. Stored, untreated manure can move towards treatment, and treated manure can flow to a storage component. Treated manure can be used to remove untreated manure from the collection system, by way of a transfer component. Manure handling systems can become very complex. They may have several flow paths with multiple components along each path.

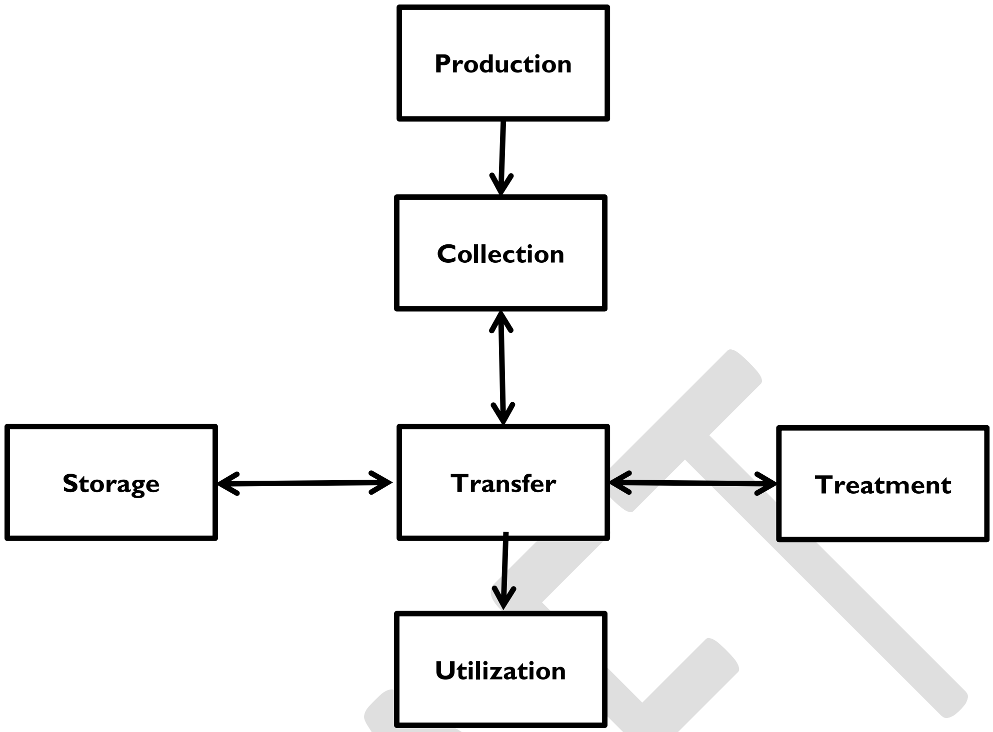

Figure TT.1. Schematic Representation of Manure Handling Systems (from Figure 9-2 in USDA NRCS, 1992).

The Role of Treatment in Manure Handling

Treatment components alter manure to make the system operate more efficiently, to reduce nuisance conditions, and to allow better utilization of nutrients by the environment. They may make manure easier to handle by separating the waste stream into a high and a low solids stream. They may alter manure organic matter to reduce odors. They may extract energy from manure organic matter. They may alter the form or concentration of plant nutrients to prepare manure for utilization by crops. They may concentrate nutrients and stabilize organic matter so that manure may be transported greater distances away from the farm. With rare exceptions, removing nutrients from the waste stream is not the intended purpose of manure treatment technologies.

The Importance of Manure Consistency

Consistency is a measure of how material maintains its shape. Figure TT.2 shows the four states of manure consistency based on its storage and handling requirements. Manure consistency is highly dependent on the species of animal that produced the manure, the diet of the animal, and moisture content. In general, the higher the moisture content, the more the manure behaves as a liquid. The higher the solids content, the more it behaves as a solid. Manure consistency has a huge effect on how manure transfer components are selected and implemented. Whether manure is scraped, pumped, squeegeed, or augured depends on its consistency. Treatment components are also heavily dependent on manure consistency. Some

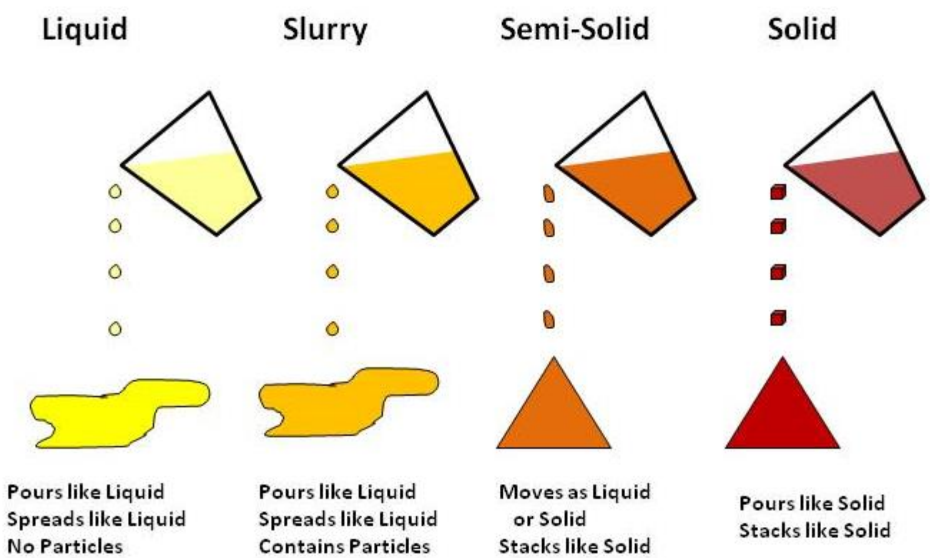

Figure TT.2. The Four States of Manure Consistency (from Hamilton, 2011b)

treatment components only operate on certain consistencies of manure. Others are more versatile, operating over a wide range of manure consistency.

Incorporation of Treatment into Chesapeake Bay Modelling Tools

The current version of Scenario Builder estimates nutrient applications to crops on a monthly basis. The monthly nutrient needs for each crop in each county are estimated based upon acres of crops reported in the county. The monthly nutrient need of each crop can be met by organic nutrients (manure and biosolids) and inorganic nutrients (fertilizer). Nutrient application relies heavily upon the amount of manure available in a county. Scenario Builder contains 14 types of animals and makes assumptions for animal weight, manure generation, and nutrient content based on the best available sources. The vast majority of nutrients from manure in the watershed are generated by poultry, dairy, beef, and swine. The amount of manure nutrients can be adjusted by various BMPs (Hanson and Johnston, 2014).

Figure TT.3 illustrates how manure BMPs are incorporated into the modeling tools. Manure treatment technologies fit into this framework in three ways 1) as BMPs reducing the amount of nutrients stored on AFOs and CAFOs, 2) by influencing the manure transport BMP by making manure nutrients more likely to be transported over county lines, 3) as BMPs transforming nutrients and making them generally more available to crops.

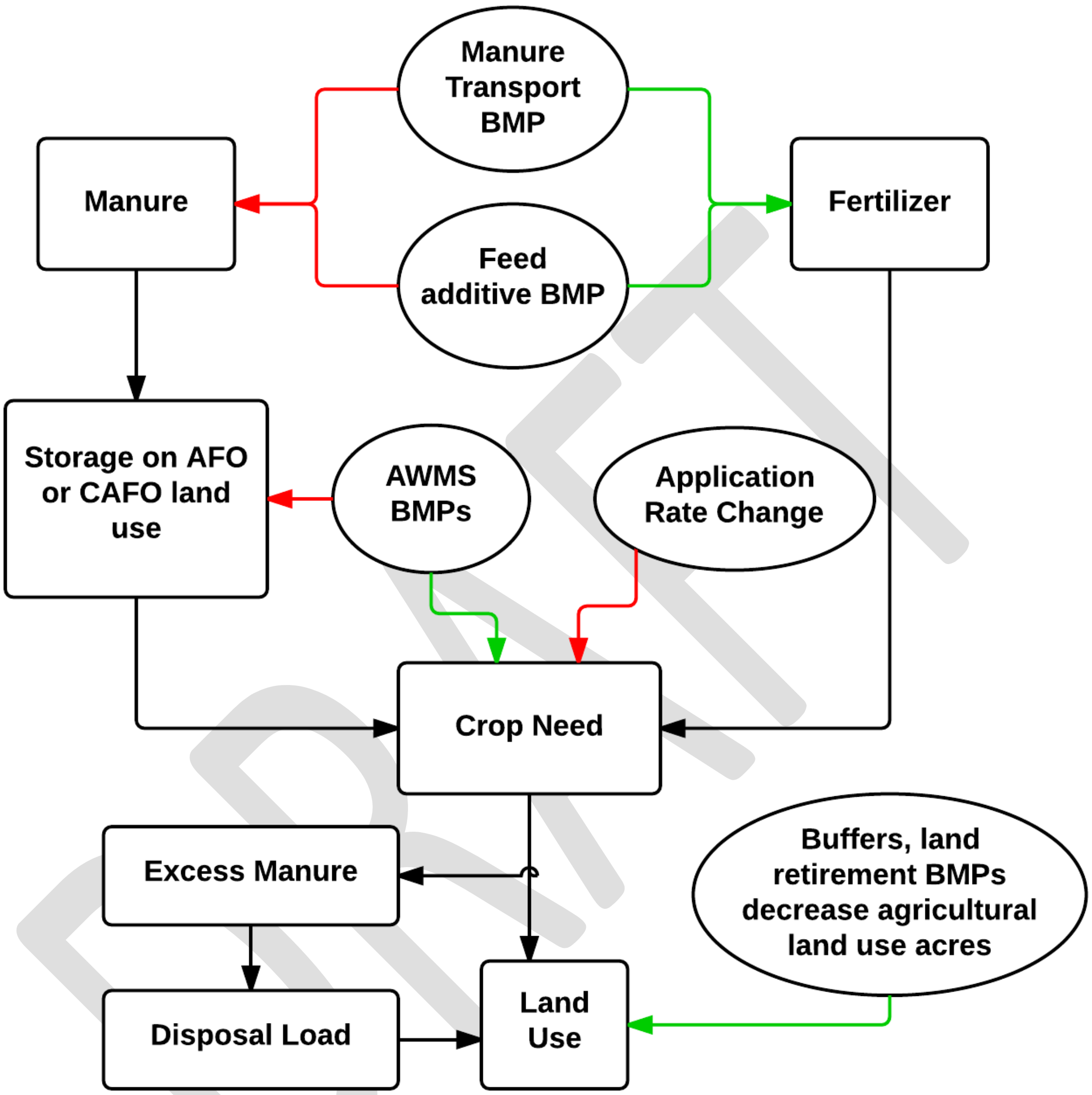

***Figure TT.3. Incorporation of BMPs into Chesapeake Bay Program Modelling Tools* (from Devereux, 2013).** Red arrows indicate decreasing amounts; green arrows indicate increasing amounts; black paths indicate calculation procedures in Scenario Builder.

Nutrient Transfer

The panel chose to approach each manure treatment technology as a Black Box (Figure TT.4). As shown in Figure TT.4.1, nutrients are not typically ***removed*** by manure treatment technologies. Rather treatment technologies ***transfer*** manure nutrients to three possible flow paths (arrows leaving box in Figure TT.4). Nutrients (both nitrogen and phosphorus) often remain in treatment flow paths to be utilized on-farm via application to crops and pasture. Nitrogen can be transferred (volatilized) to the atmosphere (dashed arrow in in Figure ES. 1) as either nitrogen gas (N_2), ammonia (NH_3), or various oxides of nitrogen (NO_x). Nutrients (both nitrogen and phosphorus) can be separated from the main manure flow path and transferred to another flow path, which is more likely to be utilized off-farm.

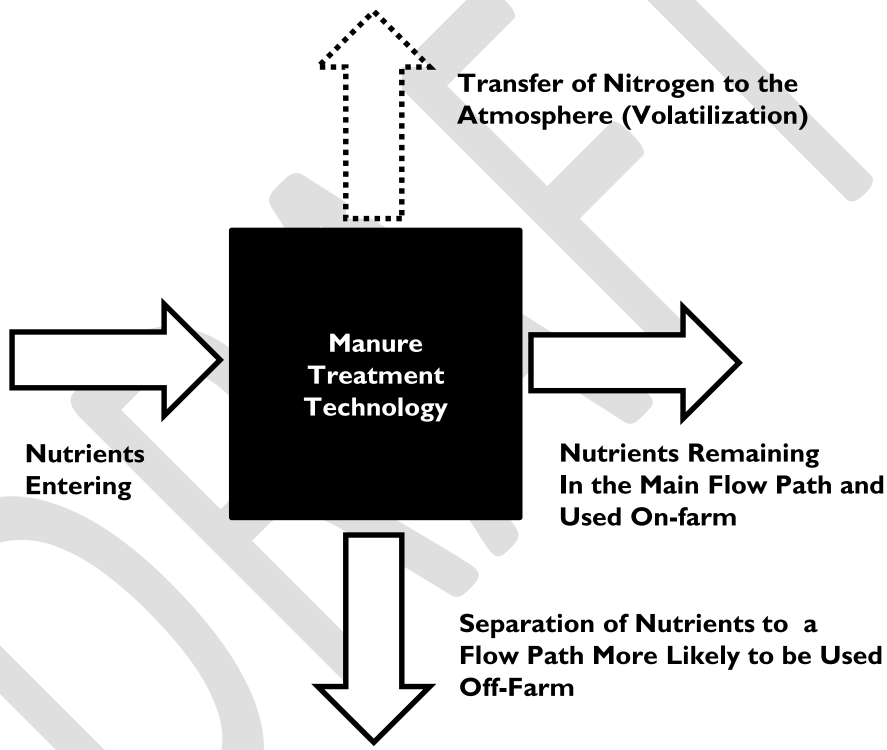

Figure TT.4. Manure Treatment Technologies as a "Black Box"

Now, consider the three flow paths in the context of Scenario Builder (TT.3). A manure treatment technology may reduce the mass of N stored for land use by transferring manure N to the atmosphere. A manure treatment technology can influence how much manure N and P is available for use in the Manure Transport BMP by transferring those nutrients to a separate, more transportable flow path.

The panel chose Mass Transfer Efficiency as the method to express how manure treatment technologies alter nutrient flows. In terms of the black box given in Figure TT1, mass transfer efficiency is calculated as:

$$\textbf{Mass Transfer Efficiency} = \frac{\textbf{(Mass of Nutrients in a Flow Path Leaving the Box)}}{\textbf{(Mass of Nutrients Entering the Box)}} \times 100 \qquad \text{TT.1}$$

Three specific transfer efficiencies were calculated for each technology: Nitrogen Volatilization Efficiency (NVE), Nitrogen Separation Efficiency (NSE), and Phosphorus Separation Efficiency (PSE). Equations used to calculate these efficiencies are given in TT.2, TT.3, and TT.4.

$$\textbf{NVE} = \frac{\textbf{(Mass of Nitrogen Transferred to Atmosphere)}}{\textbf{(Mass of Nitrogen Entering the Treatment Technology)}} \times 100 \qquad \text{TT.2}$$

$$\textbf{NSE} = \frac{\textbf{(Mass of Nitrogen Separated from Main Flow Path)}}{\textbf{(Mass of Nitrogen Entering the Treatment Technology)}} \times 100 \qquad \text{TT.3}$$

$$\textbf{PSE} = \frac{\textbf{(Mass of Phosphorus Separated from Main Flow Path)}}{\textbf{(Mass of Phosphorus Entering the Treatment Technology)}} \times 100 \qquad \text{TT.4}$$

Nutrient mass is expressed as total nitrogen (TN) and total phosphorus (TP) throughout this report. Also, mass transfer efficiency is expressed as a percent; however, these efficiencies may also be considered fractions. To determine the mass of N or P transferred by a manure treatment technology, multiply the mass entering by transfer efficiency and divide by 100. To determine the mass leaving in the main flow path, subtract mass entering by mass transferred to atmospheric and separation flow paths.

Nutrient Transformation

The third influence manure treatment technologies have on modelling tools is by transforming nutrients. While converting manure organic matter to carbon dioxide (CO_2) and water (H_2O), treatment technologies also convert organic N and P to inorganic forms. The transformation of organic nutrients to more soluble, inorganic forms makes the nutrients more available to crops, and potentially, more susceptible to environmental losses. Other treatment technologies cause the precipitation of soluble N and P to less soluble salts. Transformation to inorganic salts affects plant uptake and nutrient losses by allowing nutrients to be stored in the soil and slowly released over time.

Nutrient transformations require looking into the inner workings of a given manure treatment technology black box. The panel acknowledges the ability of manure treatment technologies to transform nutrients. Data provided in the literature on nutrient transformation is reported in each technology chapter. However, since the effect of nutrient transformation is seen during storage or land application –which is outside the expertise and charge of this panel– the panel did not provide specific numeric transformation performance estimates for each manure treatment technology considered here.

How to Use Recommendations in this Report

Each manure treatment technology chapter in this report is broken into the following sections:

1. A short definition of the technology
2. Definitions of terminology used with the technology.
3. Detailed description of the types of technology evaluated by the panel
4. Short descriptions of related technologies not evaluated by the panel
5. Types of manure treated by the technology
6. Definition of mass transfer efficiencies as used for the particular technology.
7. Default transfer efficiencies to use in Scenario Builder (Level I)
8. A thorough review of the literature on effectiveness of each technology (including nutrient transformation)
9. Defined mass transfer efficiencies to use in Scenario Builder if process factors are known for a particular farm (Level II)
10. Ancillary benefits of using the technology
11. Potential environmental hazards posed by the technology
12. List of references used in compiling the information given in the chapter.

Mass Transfer Efficiency Recommendations

Two levels of mass transfer efficiencies are recommended for use by the Chesapeake Bay Program:

1. **Default Transfer Efficiency** (Level 1) to be used when the only things known about a treatment system are the manure and treatment technology type.

2. **Defined Transfer Efficiency Value** (Level 2) to be used when the manure type is known and pertinent operating conditions of the treatment technology are known.

In addition, actual monitoring data for an individual operation may be used if monitoring data exists for the treatment system. With monitoring in hand, a third value may be used:

3. **Data Driven Transfer Efficiency** (Level 3) to be used when actual monitoring data for a particular farm is available.

Use of monitoring data is covered in Section 10, Data Collection and Reporting Protocols for Reporting Data Driven (Level 3) Transfer Efficiencies.

Combinations of Several Technologies

More than one manure treatment technologies may be used in a manure handling system. To determine the effect of several technologies on nutrient transfer, remember that mass transfer efficiencies are multiplicative for technologies combined in series. Figure TT.5 demonstrates this principle. A swine farm uses flushing to remove manure from buildings. Flushed manure enters a clarifier (a settling technology). Liquids leaving the clarifier is stored and irrigated onto

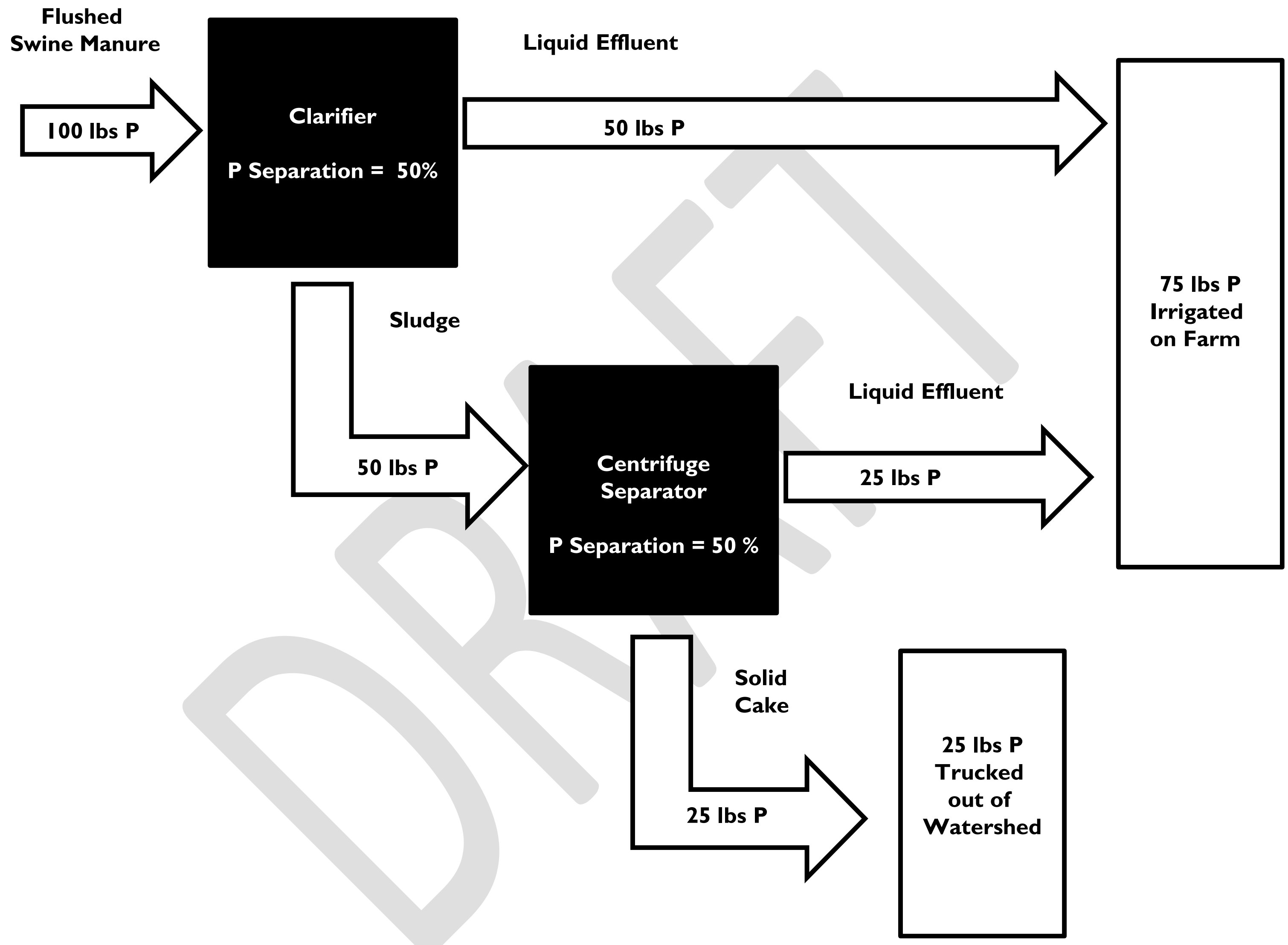

Figure TT.5. Combined Effect of a Clarifier and Centrifuge Working in Series on the Separation ~~Removal~~ of Phosphorus from Flushed Swine Manure.

cropland on the farm. Sludge leaving the clarifier enters a centrifuge (mechanical solid-liquid separation technology) which further thickens the sludge slurry into a solid cake. Liquids leaving the centrifuge are stored and irrigated along with the clarifier effluent. Both the clarifier and the centrifuge have a phosphorus separation efficiency of 50%, meaning half of the TP entering the black box exits in a flow path that is more likely to be used off-farm. Separation efficiency of the combined treatments is 25%, because 75% of the TP excreted by pigs remains on farm, while 25% is trucked out of the watershed.

Compatibility of Technologies and Manure Types

Not all technologies will be used on every single type of manure found in the Chesapeake Bay watershed. Consistency of manure in the handling system is a major factor determining use of technology. Table TT1 is a matrix of compatibility between technologies, manure consistency, and type of livestock housed on a farm. The manure types given in Table TT1 is not meant to be an exhaustive list, but a listing of the major types of manure contributing nutrients to the Chesapeake Bay. Some minor manure types can be used with the technology. For instance, composting is widely used to treat horse manure and horse stall cleanings in the Chesapeake Bay Watershed.

Table TT.1. Compatibility of Manure Treatment Technologies Covered in this Report with Major Manure Types Found in the Chesapeake Bay Watershed. Black rectangles indicate that the technology is mostly compatible with the manure. Grey rectangles indicate that the technology is compatible but with major pretreatment to the manure. White rectangles indicate that the technology and manure are incompatible.

	Thermo-chemical Processing	**Composting**	**Anaerobic Digestion**	**Settling**	**Mechanical Solid-Liquid Separation**	**Wet Chemical Treatment**
Semi-Solid Dairy						
Slurry Dairy						
Liquid Dairy						
Slurry Swine						
Solid Poultry						

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4. Thermochemical Conversion Processes

Thermochemical conversions (TCC) Processes are high-temperature chemical reforming processes that convert organic matter into a combination of synthesis gas, bio-oil, and char/ash (McKendry 2002; Kambo and Dutta 2015).

Thermochemical Conversion Terminology:

Synthesis Gas (Syngas) is a mixture of water vapor (H_2O), Hydrogen (H_2), Carbon monoxide, (CO), Carbon Dioxide (CO_2), Nitrogen (N_2), hydrocarbon gases, tars, and other contaminants. Once cleaned of dust, tars, metals, water and organic acids, Syngas can serve as a fuel gas or bioenergy feedstock.

Bio-Oil is the highly oxygenated condensation product of synthesis gas. Bio-oil has combustible qualities allowing it to be utilized potentially as a fuel source or bioenergy feedstock.

Char/Ash is the un-volatilized, solid residual of thermochemical conversion. It is a combination of minerals and fixed carbon. Manure based char is a nutrient-dense material that has potential as an alternative fertilizer or soil amendment (Cantrell et al 2012). Following the biochar standards published by the International Biochar Initiative (IBI), **Biochar** contains more than 10% organic carbon (International Biochar Initiative 2014). For the purposes of this report, the solid by-product from thermochemical processes with less than 10% organic carbon is termed **Ash**.

Types of Thermochemical Processes

Combustion (Figure TCC.1) is the direct consumption of dry manure to produce heat without generating intermediate fuel gases or liquids. Combustion temperatures range between 1,500 and 3,000 °F (820 to 1,650°C). Usually, excess air is supplied to ensure maximum fuel conversion. Combustion produces CO_2, H_2O, ash, and heat, with the heat typically used for steam production. During complete combustion, all organic material is oxidized to CO_2 and H_2O. Incomplete combustion can produce pollutants such as CO, particulates, and volatile organic compounds (VOCs). Additionally, nitrogen and sulfur in manure and high combustion temperatures can lead to emissions of oxides of nitrogen and sulfur (NOx and SOx).

Figure TCC1. Blue Flame Combustion Boiler on Poultry Farm in Chesapeake Bay Watershed (USDA NRCS).

Gasification (Figures TCC.2 and TCC.3) is the thermochemical reformation of biomass at temperatures between 1,870 and 2,730°F (1,000 to1,500°C) in a low oxygen or starved oxygen environment, using air or steam as reaction medium. The main purpose of gasification is to produce syngas. Syngas produced by gasification is primarily CO, H_2, Methane (CH_4), and other light weight hydrocarbons. By-products of gasification include trace liquids (tars, oils, and other condensates) and minor amounts of char or ash. The amount of char produced in gasification depends on the ash content of the feedstock. Syngas can be used in internal combustion engines or used to produce other fuels such as bio-diesel. Combustion of syngas results in the same end products as direct combustion of manure, but with improved pollution control, conversion efficiencies, and easier fuel storage and handling. There are several gasification configurations; design is dependent of the desired application and by-products.

Figure TCC.2. Enginuity Gasification System on a Poultry Farm in the Chesapeake Bay Watershed (USDA NRCS).

Figure TCC.3. Energy Works Gasification Facility near Gettysburg, PA (USDA NRCS).

Pyrolysis (Figure TCC.4) is the conversion of organic matter in the absence of oxygen at temperatures between 575 and 1,475°F (300 to 800°C). Organic matter is broken down to produce some combination of liquids, gases, and solids. The desired functionality of the end product will drive the type of pyrolysis process. **Fast Pyrolysis** has a short residence time (seconds) and moderate temperatures, and is primarily used to produce bio-oil (up to 75% by weight of feedstock) (Bridgwater and Peacocke, 2000). **Slow Pyrolysis** has longer residence times (hours to days) and lower temperatures and is used to produce char. Syngas formed during pyrolysis is a mixture of H_2, CO, CO_2 and lesser amounts of H_2O, CH_4, and other light hydrocarbons. The energy content of pyrolysis syngas can vary from 40 to 77% that of CH_4 (Roet al., 2010). Syngas is converted to useable energy through direct burning or operation in a combined heat and power (CHP) system. Pyrolysis oils can be used as boiler fuel or refined similar to crude oil. Biochar can be used similar to charcoal or as a soil amendment. Combustion of pyrolysis liquids and gases result in the same end products as direct combustion of manure, but with improved pollution control, conversion efficiencies, and easier fuel storage and handling. Minimal oxygen requirements reduce the formation of emission pollutants.

Figure TCC.4. Virginia Tech Pyrolysis Unit (USDA NRCS).

Other Thermochemical Processes not Covered in this Report

Hydrothermal Processes are used to convert wet manure and sludge such as those produced by swine and dairy operations. Hydrothermal techniques include **Hydrothermal Liquefaction (HTL)** and **Hydrothermal Carbonization (HTC)** (Cantrell et al., 2007; Libra et al., 2011; He et al., 2000). In HTL, aqueous organic matter is converted to organic oils by applying relatively low heat (475 to 750 °F; 250 to 400 °C) and high pressure. He et al. (2000) reported swine manure conversion at 90 atm). The desired product of HTC is carbon-rich biochar. Hydrothermal carbonization is performed at slightly lower temperatures (compared to HTL), where the reaction pressure is equivalent with the saturation vapor pressure of water. To date, hydrothermal processes have been limited to laboratory scale operations.

Types of Manure Used

Combustion, pyrolysis, and gasification are used to convert drier wastes such as poultry and turkey litter. Wetter materials, such as slurry or semi-solid dairy and swine manure must undergo desiccating pretreatment (solid-liquid separation, composting, or air drying) before conversion by pyrolysis and gasification. Pretreatment processes may be energy intensive and reduce the economic and energetic efficiency of the overall process.

Transfer Efficiencies of Thermochemical Conversion Processes

Thermochemical Conversion Processes are shown as a black box in Figure TCC.5. By definition, all of the manure entering a thermochemical conversion process is transformed to ash, char, or bio-oil. There is not a stream of manure leaving the black box in Figure TCC.5., because the dry manure entering has all been transformed to ash, char or bio-oil. The nitrogen and phosphorus contained in ash or char is more likely to be utilized off-farm compared to nutrients contained in the original manure, hence the arrow for N and P in ash and char is pointing downward, indicating that these nutrients have been separated from the main manure flow. The second arrow leaving the box indicates the mass of N volatilized and transferred to the environment as a component of syngas. Bio-oil is almost always used in a secondary gasification or combustion process. Nutrients contained in bio-oil, therefore, exit the black box in the syngas stream.

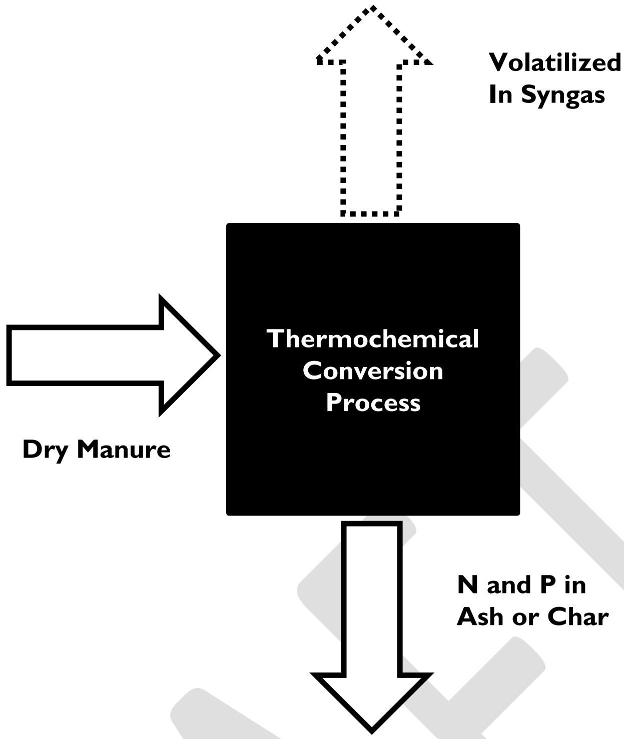

Figure TCC.5. Thermochemical Conversion Black Box Process

The three transfer efficiencies for thermochemical processes are defined in the terms of Figure TCC.5 as:

$$\text{NVE} = \frac{\text{(Mass of TN in Syngas)}}{\text{(Mass TN in Dry Manure)}} \times 100 \qquad \text{TCC.1}$$

$$\text{NSE} = \frac{\text{(Mass of TN in Ash or Char)}}{\text{(Mass TN in Dry Manure)}} \times 100 \qquad \text{TCC.2}$$

$$\text{PSE} = \frac{\text{(Mass of TP in Ash or Char)}}{\text{(Mass TP in Dry Manure)}} \times 100 \qquad \text{TCC.3}$$

Default Transfer Efficiencies for Thermochemical Processes

Without detailed knowledge of the process factors for a particular treatment system, the default Nitrogen Volatilization Efficiencies (NVE), Nitrogen Separation Efficiencies (NSE) and Phosphorus Separation Efficiencies (PSE) listed in Table TCC.1 should be used as inputs to the Chesapeake Bay Model. If the operating temperature and holding time of the process is known, values in Table TCC.5 may be used.

Table TCC.1. Default Transfer Efficiencies for Thermochemical Conversion Processes.

Thermochemical Conversion Process	Transfer Efficiency (%)		
	NVE	NSE	PSE
Combustion	85	15	100
Gasification	85	15	100
Pyrolysis	25	75	100

Review of Available Science on Thermochemical Conversion Processes

The primary thermochemical conversion processes currently evaluated and utilized within the Chesapeake Bay Watershed are combustion, gasification and pyrolysis. Combustion of manure yields heat that must be used immediately; thus, this method does not provide a storable energy product. As such, pyrolysis and gasification have been the focus of most research, largely due to their product versatility. Table TCC.2 shows the defining control parameters of each thermochemical conversion process. Major end products of each process and their relative distribution range are given in Table TCC.3. The values shown in Table TCC3 are meant to be a qualitative comparison of the technologies rather than a quantitative reference on product distribution (Boateng et al, 2015). Quantity and quality of end product are dependent on operating temperature, reaction medium, heating rate, residence time, and ash content of feedstock. Feedstock particle size, mode of operation (batch or continuous), heating technique, and feedstock homogenization are secondary process factors affecting the efficiency of operation. Approximate percent of feedstock total solids, total nitrogen, and total phosphorus based on feedstock dry matter, ash content, and temperature range is given in Table TCC.4.

Process Factors

Operating Temperature plays a major large role in the ~~removal~~ volatilization of N from manure handling systems. Combustion systems typically operate at high temperatures (>1500˚F) and with excess oxygen associated with the process, much of the nitrogen is converted to various gaseous forms. Gasification processes cover a wide range of temperatures. Generally, as the operating temperature is reduced, the amount of nitrogen retained in the ash/char increases. Below 1,500° F, 75% of manure N is retained in char. Above 1,500° F, as much as 85% of manure N is lost in gaseous emissions. Even though nitrogen retention in ash/char does not have the drastic change at a given temperature, using 1500˚F provides a guide to use for systems without monitoring or testing data. This temperature could also vary depending on the system and operational performance.

Reaction Medium is an easy parameter with which to categorize heat treatment processes. In order to consume all the reactionary portion of the feedstock, combustion processes operate under an excess of oxygen. Gasification operates with a nominal amount, usually sub-stoichiometric, of O_2. Pyrolytic processes operate without O_2 present. As more oxygen is added to the system, more gases are released -- including the volatile gases Ammonia (NH_3) and light hydrocarbons.

Table TCC.2. Thermochemical Conversion Processes Conditions.

Thermochemical Conversion Process	Feedstock Consistency	Process Conditions			
		Temperature (°F)	Pressure (atm)	Aeration Level	Residence Time
Combustion	Solid	1,500 - 3,000	~1	Excess O_2	Minutes to Hours
Gasification	Solid	1,400 - 2,700	~1	Limited O_2	Minutes to Hours
Fast Pyrolysis	Solid	750 - 1,100	~1	No O_2	Seconds
Slow Pyrolysis	Solid	575 - 1,475	~1	No O_2	Hours to Days

Table TCC.3. Major End Product and End Product Distribution Ranges based on Ash-Free Feedstock Material for Thermochemical Conversion Processes.

Thermochemical Conversion Process	Major End Products	End Product Distribution		
		Gas	Liquid	Solid
Combustion	Heat, Ash	85 – 100	0	0 - 15
Gasification	Syngas, Char or Ash	85 – 95	0 - 5	5 - 15
Fast Pyrolysis	Syngas, Bio-oil, Bio-char	20 - 40	40 - 70	10 – 25
Slow Pyrolysis	Syngas, Bio-char	40 - 75	0 - 15	20 - 60

Table TCC.4: Percent of Feedstock Solids, Nitrogen, and Phosphorus Retained[1] in Char or Ash residual.

Thermochemical Conversion Process	Temperature Range (°F)	TS Retained in Ash/Char (%)	TN Retained in Ash/Char (%)	TP Retained in Ash/Char (%)
Combustion	1,500 – 3,000	Ash + 0.15 (100 - Ash)[2]	5	100
Gasification	1,500 – 2,700	Ash + 0.15 (100 - Ash)	15	100
Gasification	<1,500	Ash + 0.15 (100 - Ash)	75	100
Fast Pyrolysis	750 – 1,100	Ash + 0.25 (100 - Ash)	25	100
Slow Pyrolysis	575 – 1,475	Ash + 0.60 (100 - Ash)	75	100

[1]Percent Removed from Manure Handling = 100 – Percent Retained in Char or Ash Residual
[2]Ash Content of Feedstock (%TS)

Heating Rates and Residence Times are a differentiating factor between fast and slow pyrolysis. Fast pyrolysis uses heating rates that approach several hundred degrees Fahrenheit per minute or second; consequently, the residence time of fast pyrolysis is on the order of seconds to minutes. Heating rates are just a few hundred degrees Fahrenheit per hour in slow pyrolysis; therefore, the material residence time in slow pyrolysis approaches hours to days.

Ash Content of Feedstock is an important component in estimating byproduct output. The greater the ash content, the greater the ash/biochar/solid residual byproduct. The ash content of manure can either be measured directly by the operator, or a generic value can be assumed based on either the livestock type or output from another solid handling system.

Feedstock Particle Size influences heat transfer and the extent of material conversion. Larger feedstock particles (some wood pyrolysis processes use logs) require a longer residence time to ensure a uniformly converted product. Smaller particles have a larger unit volume surface area, which leads to faster burnout and higher reactor temperature (Priyadarsan et al., 2004; Cantrell et al., 2008). In fast pyrolysis, where high heating rates and short reaction times are desired, the feedstock commonly undergoes grinding to generate fine particles (Boateng et al., 2015). Whether large or small, uniform particle size is important in maintaining consistent peak temperature propagation rates. As shown in Figure TCC.5, smaller particles will achieve their internal peak temperature faster than larger particles. If two dissimilar particles are converted, there are uneven internal temperatures at a given reaction time.

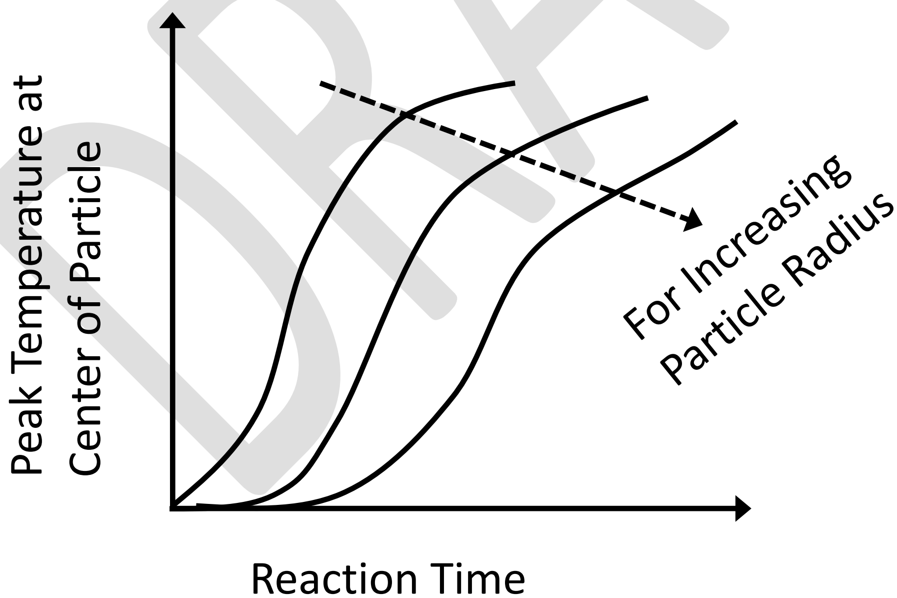

Figure TCC.5. Dependence of Time to Reach Peak Temperature on Particle Size.

Mode of Operation and Heating Technique depend on equipment and the treatment train. Batch processes focus on controlling high quality outputs such as biochar. Batch processes have large start-up and cool-down costs. Continuous operation equipment offers a constant flow of material with an even application of heat. Continuous flow units, however, require greater process controls and a more intimate knowledge of the physical processing. Heat transfer from the heat source to the feedstock may be autothermal -- the feedstock is oxidized (burned) with a direct air or oxygen source. Alternatively, heat transfer can occur through contact with hot gases or some other heat carrier (Boateng et al., 2015).

Feedstock Homogenization is necessary for quality control of the end products. Manure is extremely diverse in moisture content, ash content, and particle size distribution. Therefore, mixing, grinding, blending or pelletizing may be necessary to create uniform particle size and homogeneous feedstock. Furthermore, the ash content and composition of manures may adversely affect both the mechanical efficiency of the equipment (bed agglomeration and reduced peak temperatures) and the end-products quantity and quality (Priyadarsan et al., 2004). Homogeneously blending manures with bioenergy crops and other agricultural residues may decrease feedstock moisture content, leading to decreases in both the energy required for drying feedstock, as well as, the energy required to maintain process temperature.

Nutrient Transformations

The only true loss of solids and nutrients from thermochemical conversion processes is through creation of gaseous end products. Nutrients contained in bio-oil are lost as bio-oil is generally utilized as an energy source. Any nutrients contained in bio-oil eventually end up in gaseous form. The only portion of feedstock remaining in the manure handling system is char or ash.

Organic carbon is lost through conversion to CO_2 or other gaseous byproducts. The extent of manure sediment and volume loss due to thermochemical conversion processes is largely due to type of process and the ash content of feedstock.

One hundred percent of manure phosphorus remains in char or ash regardless of the thermochemical process used. Minor losses (less than 1%) may occur because of vaporization of phosphorous at extreme temperatures. The majority of the phosphorus in ash and char will be in inorganic form. This is a result of the carbon being removed during thermochemical conversion and cleaving any organic bonds to phosphorous. This form of phosphorous is highly soluble and capable of moving easily into a soil-water system. However, other environmental factors like the soil characteristics will influence phosphorous availability.

The typical gaseous nitrogen emissions from thermochemical processes include: ammonia (NH_3), nitrogen oxides (NO_X), nitrous oxide (N_2O), and nitrogen gas (N_2). Losses of nitrogen from the solid phase as ammonia emissions are generally less than 2% of total losses (Caron-Lassiter 2014). Additionally, based on reported air permits -(Energy Works Biopower, 2014) and available EPA air emission data (www.epa.gov/air/emissions) NO_X-N emissions can be estimated as 10% of feed N. The Farm Manure-to-Energy Initiative (2015) reported on a limited number of air emission tests which were conducted on gasification and combustion systems for litter from small poultry operations. Results show that ammonia emissions were less than 0.05% for all operations. Nitrogen oxides varied from 2.5 to 5.2% for the combustion systems and 0.6% from gasification. (A portion of the NO_X, especially for the higher operating temperatures of the combustion systems, likely resulted from thermal NO_X, but was not considered for this work.) Nitrous oxide (NO) was estimated at 2.65% of the NO_X (EPA AP-52, Chapter 1.6, 2003) which accounted for 0.1% or less of the nitrogen being emitted. Comparing these emitted values with the nitrogen retained in the ash/char (Farm Manure-to-Energy, 2015) showed that for these combustion systems, the emissions associated with N_2 was approximately 90% and for gasification at greater than 96% of the total nitrogen emissions. Similar data was not published for pyrolysis systems, but given the operating temperature and lack of oxygen it would be expected that a pyrolysis system would release more of its nitrogen in the form of N_2 than a gasification system. However, to be conservative the gasification N_2 rate of 96% could be used. The remainder of emitted nitrogen (10% for combustion; 4% for gasification and pyrolysis) would be assumed to be in reactive forms as NO_X or NH_3. The deposition fate of ammonia and NO_X may be of interest to other technical groups (e.g., the Modeling Workgroup) for adjustments in the modeling tools if desired by the partnership. These percentages only apply to emitted nitrogen and do not change the panel's analysis of the N that remains in the ash/char (Table TCC.4) that would be available for application or transport. It should be noted that these percentages are based on a very limited number of systems and are not representative of all combustion or gasification systems.

The performance and subsequently the air emissions of each thermochemical system will vary from other systems due to unique operational characteristics, e.g., the characteristics of the manure or litter fed to the system, the feed rate, the system itself, system maintenance, pre-treatment or other steps in the process, etc. The panel's recommended values represent their best attempt at a reasonable estimate for that type of technology's performance considering the potential variability. These generalized rates will serve for the CBP's purposes if the Modeling Workgroup and the CBP Partnership need to make adjustments to the Default and Defined TCC BMPs (MTT1-6) are made to account for redeposition within the watershed.
~~Gaseous emissions are considered true losses of nitrogen from the solid phase as ammonia emissions are generally less than 2% of total losses (Caron-Lassiter, 2014). Additionally, based on reported air permits (Energy Works Biopower, 2014) and available EPA air emission data (www.epa.gov/air/emissions) NOx-N emissions can be estimated as 10% of feed N. The deposition fate of ammonia and NOx may be of interest to other technical groups and/or future iterations of the model.~~

Concerns with Relevant Data

Most of the research on thermochemical processes has been bench scale. Recently, through the NRCS Conservation Innovation Grant program, several farm-scale thermochemical technologies are being evaluated within and around the Chesapeake Bay watershed. Unfortunately, within the working time frame of this working progress, project reports were not publically available or peer-reviewed. Projects are located in Pennsylvania, Virginia, West Virginia and South Carolina. All of these systems have focused on poultry systems (broiler, turkey and layer operations). From this work, preliminary results show that the nutrient concentration or loss (in relation to nitrogen) is strongly dependent on the technology used and residence time. Most resulting ash products show a reduction of nitrogen of nearly 90 percent or more and a phosphorus concentration of 7 to more than 10 times the fresh poultry litter. Processes producing bio-char or char-like products may only lose half of the nitrogen to the atmosphere and concentrate phosphorus from 2.5 to 3 times the original concentration.

Defined Transfer Efficiencies based on Process Factors

If operating temperature of a given process is known, the transfer efficiencies given in Table TCC.5 may be used as inputs to the Chesapeake Bay Model.

Table TCC5: Defined Transfer Efficiencies of Thermochemical Conversion Processes based on Process Factors.

Thermochemical Conversion Process	Operating Temperature (°F)	Transfer Efficiency (%)		
		NVE	NSE	PSE
Combustion	1,500 – 3,000	95	5	100
Gasification	1,500 – 2,700	85	15	100
Gasification	<1,500	25	75	100
Fast Pyrolysis	750 – 1,100	75	25	100
Slow Pyrolysis	575 – 1,475	25	75	100

Ancillary Benefits of Thermochemical Processes

Energy Production

Just like other plant-based biomass, there is energy in manure. As a general rule, animal manures can have energy values approaching 8,000 BTU/lb (dry basis). Table TCC5 lists typical energy values for various types of animal manure in comparison with other energy sources. This value can vary tremendously depending on the moisture and ash contents. As would be expected, the higher the moisture and ash content the lower the energy value. It should also be noted that sand and other bedding materials may influence not only the high heat value (HHV), but also the distribution and quality of thermochemical process end products.

Table TCC.6. Typical Energy Values of Manure, Biobased Products and Coal (From He et al., 2000: McKendry, 2002; Tumurulu, 2011; Cantrell et al., 2012).

Feedstock	Ash (%)	High Heat Value (BTU lb^{-1} TS db)
Dairy Manure	24.2	8,990
Beef Feedlot Manure	28.7	8,770
Swine Manure	32.5	9,080

Poultry Litter	30.7	8,180
Switchgrass	9.8	7,000
Wood Waste	42.0	5,030
Coal (Central Appalachian – Long Fork)	11.5	12,110

Transportation Efficiency

Biochar and ash represent only a small fraction of the mass and volume of the manure feedstock entering the thermochemical process. The end products are essentially free of water. Given that all of the manure phosphorus and some portion of manure nitrogen remain in the ash or char, it should be more economical to ship biochar or ash than manure due to its lower weight.

Pathogen Control

One of the many ancillary benefits of thermochemical processes is control of pathogens. Ultra-Heat Treated (UHT) milk is held at 284° F for 4 seconds. All of processes listed in Table TCC2 go far beyond UHT conditions. One could consider thermochemically processed manure "beyond pasteurization".

Potential Hazards of Thermochemical Processes

Polycyclic Aromatic Hydrocarbons (PAH) and other toxicants may be present in biochar. PAHs can be created when the thermochemical process is not complete (Office of Solid Waste, 2008). These potential solid by-products can stay in the environment for long periods of time. The effects of long term exposure to humans is not available. **Heavy Metals** may also be a concern in biochar and ash. Any heavy metals present in the feedstock will be concentrated in the ash or char following the thermochemical processing. **Errant gases** from the conversion process like NOx, SOx, and NH_3 need to be addressed in air quality permits. **Fire Hazards** may also be of concern when handling fine particles of feedstock and more importantly a powdered carbonized product. Though slow-pyrolyzed char does not have the reactive surface area as activated carbon, equivalent safe handling practices should be followed as for powdered activated carbon.

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5. Composting

Composting is the decomposition of solid organic materials in the presence of oxygen, leading to a stable product with a carbon to nitrogen Ratio (C:N) less than or equal to 25.

Composting Terminology

Compost is the solid end-product of composting that meets minimum maturity requirements with C:N less than or equal to 25. Measures of compost maturity require additional metrics as delineated by industry accepted indices (California Compost Quality Council, 2001).

Compost Tea or Leachate is the liquid byproduct of composting. Liquid leaving properly operating composting systems should have C:N less than 25.

Bulking Agent is material or media added to increase the porosity and aeration capacity of manure. Some bulking agents such as wood chips, wood pulp, sawdust, dried leaves, straw, and shredded paper also add degradable carbon to the composting mixture. These are known as **Carbonaceous Bulking Agents**. **Non-Carbonaceous Bulking Agents,** such as shredded tires, serve solely to increase compost porosity.

Co-Composting Agent is material added to manure to increase the volume and/or value of compost. A co-composting agent may or may not increase porosity and aeration. Some readily digested materials such as molasses serve as carbon sources, while others, such as food waste, increase nitrogen content and must be counterbalanced with high carbon material.

Note: The CBWM and Scenario Builder do not explicitly account for potential nutrients associated with bulking or co-composting agents, only the nutrients in the manure or litter itself are explicitly accounted for. The panel believes its recommended N reductions for composting are sufficiently conservative based on the literature that any potential or perceived discrepancy resulting from added bulking or co-composting agents will be extremely minimal.

Types of Composting Systems

Passive Piles and Windrows rely on natural aeration. Heat generated during composting rises and pulls air into the pile. Piles are turned or mixed occasionally. This is usually accomplished by moving the pile from one bin to another (Figure C.1) or moving the windrow to a new area.

Turned Piles and Windrows (Figure C.2) rely on frequent turning, usually with specialized machinery, to aerate the compost.

Figure C.1. Three Bin Passive Pile Composting Shed (Clatsop County Water Conservation District)

Figure C.2. Turned Windrow Composting (gatheringtogetherfarm.com).

Forced Aeration Piles and Windrows (Figure C.3) use mechanical ventilation to push air into or draw air through the pile or windrow.

Figure C.3. Forced Aeration Pile (from O2Compost.com).

In-Vessel Composting (Figure C.4) is performed in an insulated silo, channel, or bin using a high-rate, controlled aeration system designed to provide optimal conditions.

Figure C.4. Bin In-Vessel Composter at the University of British Columbia (myuna.com)

Rotating Drum Composters (Figure C.5) are a subset of in-vessel composters that aerate compost by turning the compost inside a rotating drum. Paddles within the drum move compost towards the outlet of the drum.

Figure C.5. Rotating Drum Composter in Delaware County, OK. (Oklahoma Cooperative Extension).

Other Composting Systems Not Covered in this Report

This report does not cover composting systems used to decompose animal mortalities. Manure, particularly poultry litter, is frequently used to inoculate **Mortality Composting**, however.

In-house windrowing of poultry litter is not considered composting in the view of the panel. Although some auto-heating takes place in the process, the piles are not operated to create marketable compost. In-house windrows are operated to achieve a small level of organic matter stabilization and fly control between flocks. This process should be a storage process rather than a treatment technology.

Vermicomposting is composting with aid of earthworms. The most common type of earthworm used in vermicomposting is *Eisenia fetida* -- commonly called Red Wigglers, Brandling Worms, Tiger Worms, Red Tiger Worms, or Lombrices Rojas Californianas. *Eisenia fetida* survive in relatively diverse conditions, are voracious eaters, multiply quickly, and have not been found to be invasive species. Vermicomposting was not considered in this report due to the small number of farm-scale vermicomposting systems currently treating manure in the Chesapeake Bay Watershed.

Types of Manure Used in Composting Systems

Composting is used to treat primarily solid or semi-solid manure such as beef and dairy cattle manure, poultry litter, horse manure, horse stall cleanings, and filter cake separated from manure slurries. Any manure can be composted if sufficient bulking agent is added to bring moisture content and C:N within acceptable ranges.

Transfer Efficiencies of Composting Systems

Composting Systems are normally placed immediately after animal confinement for solid and semi-solid manures, or after a solid-liquid separation process for manure slurries. Raw materials may also be stored before processing -- especially in a centralized facility handling manure from many farms.

Compost may be used on farm, but compost also has commercial value, making it more likely to be used off-farm as a soil amendment to landscaping, turf grasses or gardening. When retained on-farm it is primarily used in crop and pasture production. Compost tea also has value as fertilizer and it is often collected and used either on or off-farm. For these reasons, nutrients contained in compost and compost tea are shown as separated from the main manure flow stream. Nitrogen is lost through volatilization during the composting process

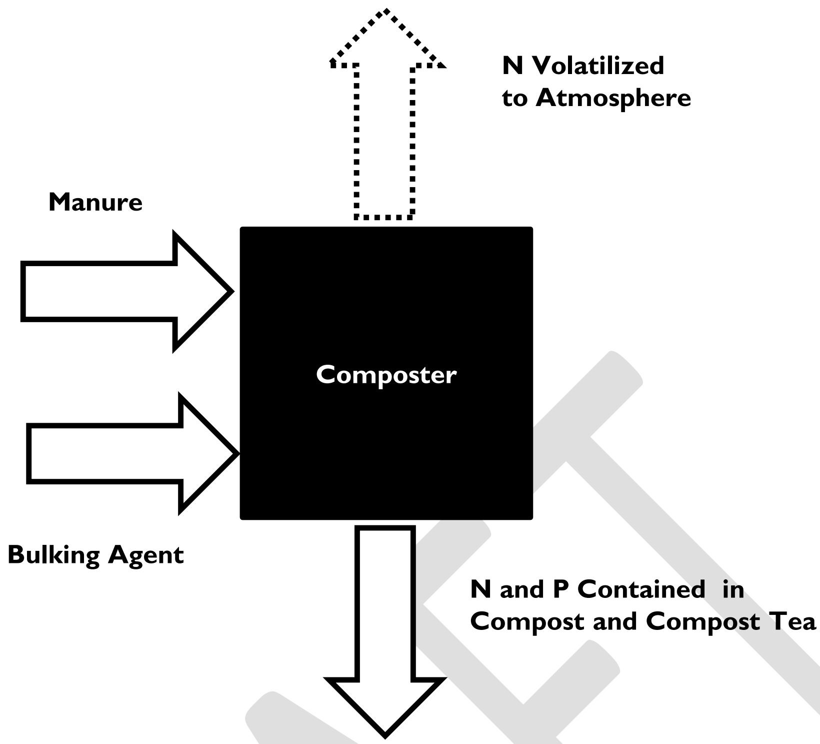

Figure C.6. Composting Black Box Process

The three transfer efficiencies for composting are defined in the terms of Figure C.6 as:

$$\text{NVE} = \frac{\text{(Mass of TN Volatalized)}}{\text{(Mass TN in Manure)}} \times 100 \qquad \text{C.1}$$

$$\text{NSE} = \frac{\text{(Mass of TN in Compost and Compost Tea)}}{\text{(Mass TN in Manure)}} \times 100 \qquad \text{C.2}$$

$$\text{PSE} = \frac{\text{(Mass of TP in Compost and Compost Tea)}}{\text{(Mass TP in Manure)}} \times 100 \qquad \text{C.3}$$

Default Transfer Efficiencies of Composting Systems

Without detailed knowledge of the process factors for a composting system, the default Nitrogen Volatilization Efficiencies (NVE), Nitrogen Separation Efficiencies (NSE) and Phosphorus Separation Efficiencies (PSE) listed in Table C.1 should be used as inputs to the Chesapeake Bay Model. If the C:N of the bulking agent is known, values in Table C.8 may be used.

Table C1. Default Transfer Efficiencies for Composting Systems.

Type of Composting System	Transfer Efficiency (%)		
	NVE	NSE	PSE
Turned Pile and Windrow	25	75	100
Static Pile and Windrow	26	74	100
In-Vessel and Rotating Bin	10	980	100
Forced Aeration	25	75	100

Review of Available Science on Composting

Compost quality is a direct product of the inputs to the composting process, which include manure and bulking agents. The major concern of compost processes is the control of C and N losses since they reduce the agronomic value of the product and, particularly in the case of N, pose environmental threats.

Initial C:N Ratio

Carbon and N compounds are most likely to limit the composting process if not present in a desirable balance. In general, 35 is considered the minimum C:N at which a sufficiently large compost pile will auto heat. Carbon to nitrogen ratios for manures generally range from 13:1 in poultry manure to 20:1 in dairy manure, with swine manure falling somewhere in between. Carbonaceous bulking agents generally have a high C:N ratios; i.e., 80:1 for yard wastes and 500:1 for woodchips. Manure provides nitrogen microbes need for protein synthesis, and carbonaceous bulking agents provide the energy needed for microbial decomposition.

Other Process Factors

Other process factors that impact composting include temperature, pH, moisture, and oxygen supply. Active management of moisture, temperature and oxygen supply is accomplished by establishing an effective turning frequency or other mechanical means of aeration. Some acceptable ranges for these factors are listed in the Table C.2., but conditions outside of these ranges may also be acceptable depending on the individual operation. The selection of bulking agents and control of optimal operating conditions affects the final product maturity and the time it takes to reach maturity. If temperature, oxygen content, porosity of the pile, or pH falls outside the optimal range for the composting process, then the overall time it takes for the compost to reach maturity will increase proportional to the time it is outside of the optimal parameters.

Table C.2. General Acceptable Ranges of Factors Affecting the Composting Process.

Factor	Acceptable Range
Temperature	130-140°F (54-60°C)
Aeration, percent oxygen	> 5%
Moisture Content	50-60%
Porosity	30-60%
pH	6.5-7.5

Compost Stability and Maturity Indices

Compost stability refers to a specific stage of decomposition during composting. Stability is related to the type of organic compounds remaining in the compost and the resultant biological activity in the material. Maturity is the degree or level of completeness of composting and is best assessed by measuring two or more parameters that describe the potential impact to plant growth. The relevance of maturity and stability parameters to assess compost quality is widely accepted throughout the literature, but there is widespread disagreement on the importance and dependability of metrics used in indices. The panel agreed that the California Compost Quality Council is a good example of an index that CBP partners could use for purposes of determining compost maturity, but other industry-accepted indices could be used if they set similar standards for the process factors described in this section. A complete list of standardized methods for sampling, analysis and quality assessments are provided by the US Composting Council in the Test Method for the Examination of Composting and Compost (TMECC) for the composting industry to verify the physical, chemical and biological condition of composting feedstocks, material in process and compost products at the point of sale (USDA, USCC 2001).

The California Compost Quality Council (2001) states all materials marketed as compost must have C:N less than or equal to 25 in order to be rated as acceptable. Maturity Rating is assigned based on two additional tests: one test is chosen from Group A, and one from Group B listed in Table C.3.

Table C3. The California Compost Quality Council Maturity Index (CCQC, 2001).

		Rating		
		Very Mature	Mature	Immature
Group A: Stability Methods				
Oxygen Uptake Rate (OUR)	$O_2\ TS^{-1}\ hr^{-1}$	< 0.4	0.4-1.3	> 1.3
Specific Oxygen Uptake Rate (SOUR)	O_2 [1]$BVS^{-1}hr^{-1}$	< 0.5	0.5 -1.5	> 1.5
Carbon Dioxide Evolution Rate	$CO_2\ VS^{-1}\ day^{-1}$	< 2	2-8	> 8
Respiration Rate	$O_2\ VS^{-1}day^{-1}$	< 5	5-14	> 14
Self-Heating Test	Temp. Rise (°C)	< 10	10-20	> 20
Group B: Maturity Methods				
Ammonium : Nitrate Ratio		< 0.5	0.5-3	> 3
Ammonia Concentration	Ppm, dry basis	< 100	100-500	> 500
Volatile Organic Acids	Ppm, dry basis	<200	200-1000	> 1000
Seed Germination	% of [2]control	> 90	80-90	< 80
Plant Trails	% of [2]control	> 90	80-90	< 80

[1]BVS – Biodegradable Volatile Solids.
[2]Control refers to germination or growth in only water or potting soil treatment.

The California Compost Quality Council (2001) suggests using maturity indices to regulate the use of compost along the following lines:

<u>Very Mature Compost</u> should be used in soil and peat-based container plant mixes, in alternative topsoil blends, and in turf top-dressing.

<u>Mature Compost</u> is recommended for general field use (pastures and hay, in vineyards and row crops, and as a substitute for low-analysis organic fertilizers where applicable.

<u>Immature Compost</u> should be used in land application to fallow soil, and feedstock for further composting.

Organic Matter Reduction ~~T~~through Composting

The second most important effect of composting, after stabilizing organic matter, is reduction in the mass and volume of manure. This reduction in mass is accomplished by removing organic carbon. Table C.4 lists the expected base removal efficiency of organic carbon of different composting systems and manure types.

Table C4. Base Organic Carbon Volatilization Efficiencies (%) of Composting Systems.

Type of Composting System	Type of Manure Composted				
	Beef	**Dairy**	**Poultry**	**Swine**	**Mixed**
Turned Pile and Windrow	35	46	35	45	35
Static Pile and Windrow	40	40	30	50	30
In-Vessel and Rotating Bin	30	30	25	35	25
Forced Aeration	15	15	9	15	9

The values given in Table C.4 are for generic composting systems with unknown bulking agents and represent base C mass removal efficiency. If the bulking agent is known to be wheat straw, cornstalks, or wood products, the base values in Table C.4 can be multiplied by the factor in Table C.5 to determine a more accurate organic carbon volatilization efficiency. For example, if a turned windrow beef manure composter uses straw as a bulking agent, multiply the value in Table C4 (base C mass removal efficiency of 35%) by 1.2 to give a carbon mass removal efficiency of 42%.

Table C.5. Factors for Modifying Organic Matter Removal Efficiencies based on Bulking Agents.

Bulking Agent	C:N	Multiplicative Factor
Wheat Straw	40:1 to100:1	1.2
Cornstalk	30:1 to 80:1	1.15
Woodchips/Sawdust	100:1 to 500:1	1.1

~~Nutrient Transformations~~

~~Much of the N in manure is transformed to microbial biomass (Org-N) during composting. Most of the remaining TN is in the form of NO_3-N in mature compost. Manure nitrogen is lost during the composting process by two pathways: 1) through liquid transport as leachate (dissolved NO_3^-), or runoff (NH_4^+ bound to particles or organic N contained in particles); and 2) through emissions of gases such as NH_3 and NO_x. The nitrogen lost through leaching can be recovered as compost tea. Most states in the Chesapeake Bay Watershed require runoff water to be contained either by covering the composting area or in a capture and reuse system. Because of these factors, the only expected loss of manure TN is through nitrogen volatilization. Sommer (2001) found that covering or compacting compost piles reduced emissions up to 18%. These practices may be considered as recommended best management~~

practices where NH_3 emissions are a concern. Table C.6 lists the expected base total nitrogen volatilization efficiency of different composting systems.

Table C.6. Base Total Nitrogen Volatilization Efficiencies (%) of Composting Systems.

Type of Composting System	Type of Manure Composted				
	Beef	Dairy	Poultry	Swine	Mixed
Turned Pile and Windrow	25	25	25	30	25
Static Pile and Windrow	28	28	26	40	26
In-Vessel and Rotating Bin	12	12	10	15	10
Forced Aeration	25	25	35	30	25

If the bulking agent or the C:N ratio of the bulking agent is known, then the base total nitrogen removal efficiencies given in Table C.6 may be adjusted by the multiplicative factors listed in Table C.7. For example, if a turned windrow beef manure composter uses straw as a bulking agent; multiply the value in Table C.7 (base value of 25%) by 1.25 to give a nitrogen mass removal efficiency of 31.25%.

Table C.7. Factors for Modifying Base Total Nitrogen Volatilization Efficiencies based on Bulking Agents.

Bulking Agent	C:N Ratio	Multiplicative Factor
Wheat Straw	40-100:1	1.25
Cornstalk	30-80:1	1.1
Woodchips/Sawdust	100-500:1	1.1

Phosphorus in compost is mainly found in inorganic fractions. Dissolved inorganic phosphorus can be lost during composting primarily as runoff, and as leachate during and following rain events. Sharpley and Moyer (2000) suggest that water extractable phosphorus may be used to estimate the potential for land-applied manure or composts to enrich leachate and surface runoff.

Nutrient Transformations

Manure **Nitrogen** is transformed to microbial biomass (Org-N) during composting. Much of the remaining TN exists as NO_3-N in mature compost. Manure nitrogen is lost during the composting process by three pathways: 1) liquid transport as leachate (dissolved NO_3^-), 2) liquid transport in runoff (NH_4^+ bound to particles or Org-N contained in particles); and 3) ~~through~~ emissions of gases such as NH_3 and NO_x. Eghball et al. (1997) found that 92% of manure TN lost from windrow composting of beef manure was through gaseous emissions, with the balance leaving in runoff and leachate.

Nitrogen lost through leaching can be recovered as compost tea. Most states in the Chesapeake Bay Watershed require runoff water to be contained either by covering the composting area or in a capture and reuse system.

Almost all of the volatilized nitrogen leaves the compost pile as NH_3. Less than 6% of nitrogen is volatilized as N_2O (Zeman et al., 2002). Ammonia emissions depend on both C:N of the pile and the concentration of easily decomposable forms of nitrogen in manure (Tiquia et al., 2000; Peigne and Biardin, 2004). Compost Piles with low initial C:N made from manure with high concentrations of Nitrate (NO_3^{-1}), urea, and ammoniacal nitrogen emit the most NH_3. Other important factors in NH_3 emission are pH and temperature. Basic compost piles with high temperatures emit more NH_3 than cool, acidic piles. Sommer (2001) found that most NH_3 losses occur during the initial 5 to 19 days of pile formation as the piles are heating. Exposure of pile surfaces to the atmosphere also increases NH_3 volatilization. Sommer (2001) found total nitrogen emissions losses were 28% for uncovered piles of deep bed dairy manure, and 12 to 18% for covered piles.

Nitrous oxide is formed during incomplete ammonia oxidation and incomplete denitrification, and high temperatures inhibit formation of N_2O (Rowan et al., 2009). Most authors found that the greatest emissions of N_2O occur in wet piles after the initial heating phase of composting, when much of the readily available carbon has been depleted. (He et al., 2001; Sommer, 2001; Amlinger et al., 2008; Brown and Subler, 2007). A few studies (Hellmann et al., 1995; Beck-Friis et al., 2000) recorded high N_2O emissions early in pile formation, but in these cases, N_2O was released by denitrification of NO_3^{-1} present in the raw materials added to the composting pile.

Table C.6 lists the expected base total nitrogen volatilization efficiency of different composting systems. This table takes into account the type of nitrogen compounds found in raw manure and the amount of exposure the compost pile experiences.

Table C.6. Base Total Nitrogen Volatilization Efficiencies (%) of Composting Systems.

Type of Composting System	**Type of Manure Composted**				
	Beef	**Dairy**	**Poultry**	**Swine**	**Mixed**
Turned Pile and Windrow	25	25	25	30	25
Static Pile and Windrow	28	28	26	40	26
In-Vessel and Rotating Bin	12	12	10	15	10
Forced Aeration	25	25	35	30	25

Low initial C:N is a critical factor affecting N loss in composting (Tiquia et al., 2000). If the bulking agent or the C:N ratio of the bulking agent is known, then the base total nitrogen volatilization efficiencies given in Table C.6 may be adjusted by the multiplicative factors listed in Table C.7. For example, if a turned windrow beef manure composter uses straw as a bulking agent; multiply the value in Table C.7 (base value of 25%) by 1.25 to give a nitrogen mass volatilization efficiency of 31.25%.

Table C.7. Factors for Modifying Base Total Nitrogen Volatilization Efficiencies based on Bulking Agents.

Bulking Agent	**C:N Ratio**	**Multiplicative Factor**
Wheat Straw	40-100:1	1.25
Cornstalk	30-80:1	1.1
Woodchips/Sawdust	100-500:1	1.1

Phosphorus in compost is mainly found in inorganic fractions. Dissolved inorganic phosphorus can be lost during composting primarily as runoff, and as leachate during and following rain events. Sharpley and Moyer (2000) suggest that water extractable phosphorus may be used to estimate the potential for land-applied manure or composts to enrich leachate and surface runoff.

Defined Transfer Efficiencies Based on Process Factors

If the C:N of the bulking agent used in a particular composting system is known, the defined transfer efficiencies given in Table C.8 may be used for input into the Chesapeake Bay Model.

Table C8. Defined Transfer Efficiencies based on Composting System and C:N of Bulking Agent.

Type of Composting System	C:N of Bulking Agent <100			C:N of Bulking Agent >100		
	Transfer Efficiency (%)			Transfer Efficiency (%)		
	NVE	NSE	PSE	NVE	NSE	PSE
Turned Pile and Windrow	32	68	100	28	72	100
Static Pile and Windrow	33	67	100	29	71	100
In-Vessel and Rotating Bin	13	87	100	11	89	100
Forced Aeration	32	68	100	28	72	100

Ancillary Benefits of Composting

Land Application

By definition, finished compost has C:N at or below 25. At this C:N, compost will not remove N from the soil. Many types of manure, such as horse stall cleanings have C:N much higher than 25. If these highly carbonaceous materials are land applied, they may rob nitrogen from the soil – soil microorganisms that decompose carbonaceous use soil N in order to digest the added carbon.

The stabilized organic matter in mature compost reduces nuisance conditions during application. The less odorous organic matter does not draw flies or complaints from the neighbors.

Depending on the amount and type of bulking agent used, compost used for land application may have less volume and mass than the original manure. This means less material must be hauled out to the fields.

Marketing Potential

Composting should result~~s~~ in a reproducible product of known quality. This attribute along with the stability of organic matter increases the likelihood that compost will be transported greater distances than raw manure and potentially out of the watershed~~ than raw manure~~.

Pathogen Reduction

During the initial stages of composting, temperature within a composting bin may reach between 130 to 140° F. Completeness of pathogen kill depends on length of time the compost is heated, as well as, how well the material is mixed during heating. Rotating bin composters have an advantage in this area, because if sufficiently large and insulated the entire contents of the bin will be heated and turning ensures complete mixing.

Potential Hazards of Composting

Bin Leachate

If compost tea is not contained, organic matter and nutrients can leach into groundwater or runoff to surface water. For this reason, most states require farm-scale composting units to be constructed under roof or on top of an impermeable surface. If open to the atmosphere, all runoff from the compost area should be contained, stored, and either treated or recycled to the compost pile.

Nitrogen Emissions:

If composting is not complete nitrogen may leave the pile in the form of ammonia gas. If the pile contains anoxic areas and denitrification is not complete, nitrogen may be emitted as N_2O gas, which is a potent greenhouse gas.

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6. Anaerobic Digestion

Anaerobic Digestion uses naturally occurring microorganisms to rapidly decompose organic matter in the absence of oxygen, forming biogas.

Anaerobic Digestion Terminology

Biogas is the gaseous material produced during the complete anaerobic breakdown of organic matter. Biogas is a mixture of Methane (CH_4), Carbon dioxide (CO_2), and other minor, but not insignificant gases: Hydrogen (H_2), Hydrogen sulfide (H_2S), Water Vapor (H_2O) and Volatile Fatty Acids (VFA). Methane is flammable with a high heat value of 1,000 BTU ft^{-3}. The energy content of biogas is dependent upon its methane content and is generally within the range 400 to 700 BTU ft^{-3}.

Influent is the liquid, slurry, or semisolid material entering a digester. The digestible, organic portion of influent is called **Substrate**.

Sludge is the material that settles in digestion reactors. Sludge may also refer to the portion of settled material that is removed from the reactor. Sludge is a mixture of active microorganisms, digested substrate, and inert material.

Effluent is the treated material leaving an anaerobic digester. Effluent may be a mixture of sludge and treated liquids, or simply the liquid portion of a reactor's content. Effluent may be liquid, slurry, or semi-solid in consistency. Effluent is sometimes referred to as 'Digestate'.

Co-Digestion Substrates are highly digestible organic materials added to influent to increase biogas production.

Types of Anaerobic Digesters

Complete Mix Digesters (Figure AD.1) are mixed so that sludge is completely suspended in the reactor vessel. The volume of effluent leaving a complete mixed digester is equal to the amount of influent entering. **Intermittent Mixed Digesters** are a subcategory of completely mixed digestion in which mixing is pulsed, and sludge is allowed to settle for extended periods between mixing. Complete mix digesters work best when manure contains 3 to 6% solids. At lower solids concentrations, the digester volume must be comparatively larger, and the energy required to mix and heat the reactor may exceed the energy available in biogas.

Figure AD.1. Complete Mix Anaerobic Digesters Treating Dairy Manure Slurry and Food Waste near Madison, WI. (Oklahoma Cooperative Extension Service).

Plug Flow Digesters (Figure AD.2) are similar to complete mix digesters in that manure flowing into the digester displaces digester volume, and an equal amount of material flows out. However, the contents of a plug flow digester are thick enough to keep particles from settling. Manure moves through the digester as a plug, hence the name "plug flow". Plug flow digesters do not require mechanical mixing. Total solids content of manure should be at least 15%, and some operators recommend feeding manure with solids as high as 20%. This means operators may need to add extra material to increase the solids content of manure to use a plug flow digester. In some designs, effluent is returned to the head of a plug flow digester to inoculate the substrate with actively growing microbes.

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Figure AD.2. Plug Flow Anaerobic Digester Located on the Schrack Family Dairy Farm in Clinton County, PA (Penn State Extension).

A **Mixed Plug Flow Digester** is a patented variation on a plug flow digester in which manure flows down a hairpin raceway (Figure AD.3). The contents are heated along the central divider and pressurized biogas is reintroduced into the reactor so that manure mixes in a corkscrew pattern as the plug flows down the hairpin.

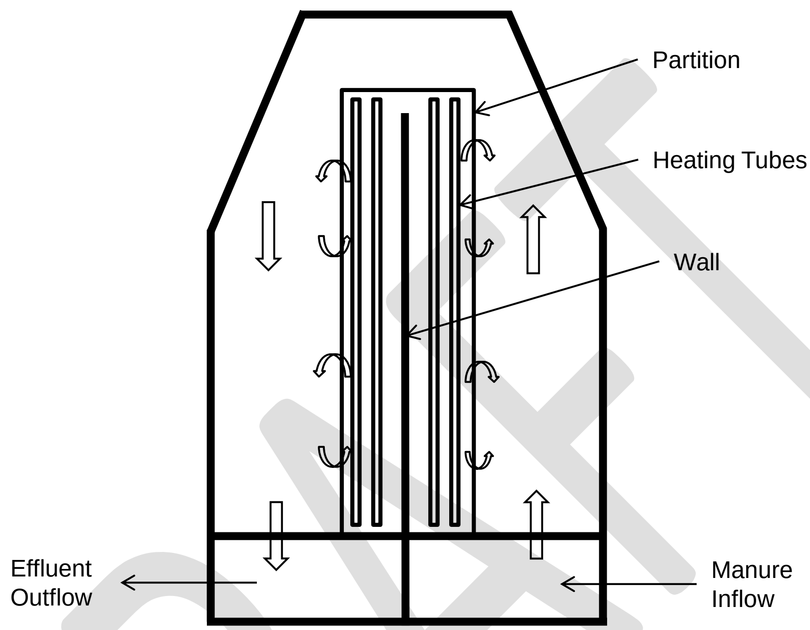

Figure AD3. Birds Eye Schematic Diagram of Mixed Plug Flow Anaerobic Digester based on US Patent 8,202,721 (From Hamilton, 2014b).

Covered Lagoon Digesters take advantage of the low maintenance requirement of a lagoon while capturing biogas under an impermeable cover (Figure AD.4). The first cell of a two-cell lagoon is covered, and the second cell is uncovered (Figure AD.5). Both cells are needed for the system to operate efficiently. The liquid level of the first cell remains constant to promote efficient manure breakdown. The second stage acts as storage and its liquid level will vary as effluent is removed for land application. Sludge may be stored in the first cell of covered lagoon digesters for up to 20 years. Storing sludge in the first cell also means much of the fertilizer nutrients, particularly phosphorus, remain trapped in the covered lagoon until sludge is cleaned from the cell. It is very costly to heat covered lagoons for optimal biogas production. The temperature of covered lagoons follows seasonal patterns; therefore, they are sometimes called **Ambient Temperature Digesters,** Because of their reliance on ambient temperatures covered lagoon digesters are more common in regions south of the Chesapeake Bay watershed.

Figure AD4. First Cell of a Covered Lagoon Digester System Located on the Oklahoma State University Swine Research and Education Center (Oklahoma Cooperative Extension Service).

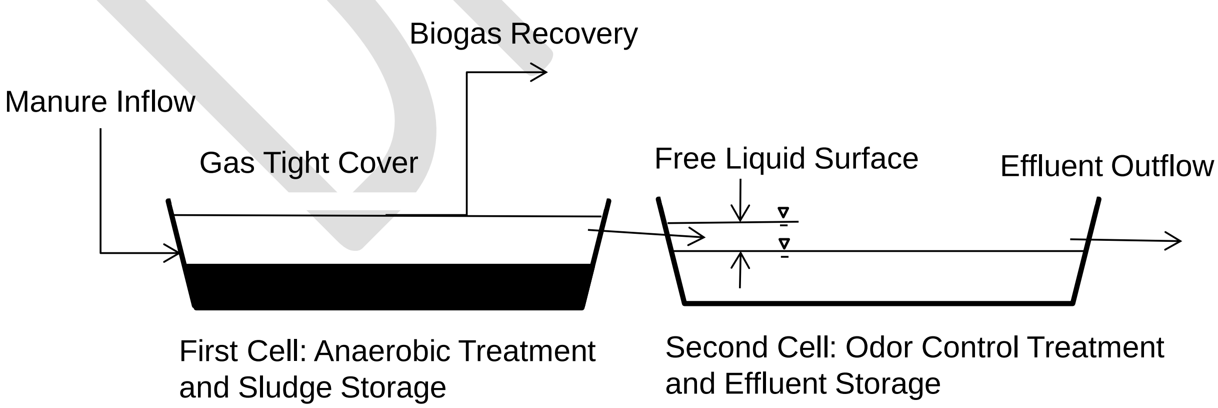

Figure AD5. Schematic Drawing of a Covered Lagoon Digester (From Hamilton, 2014b)

Other Digestion Systems not covered in this Report

Anaerobic digesters can be arranged in single stage (all processes taking place in one reactor vessel) or multi stage systems (separated reactors for different processes). For the purposes of this report, we will only consider single stage complete mix, plug flow, mixed plug flow, and covered lagoon digesters. The other digestion systems described below may become more common on farms in the Chesapeake Bay Watershed.

High Rate Systems are digesters that increase biogas production efficiency by retaining living biomass in the digestion reactor. **Fixed Film Reactors** are digesters in which biogas producing microorganisms are cultivated in biofilms growing on solid media in the reactors, **Contact Stabilization Reactors** are digesters in which biologically active solids are recycled back to the reactor after settling or centrifuging effluent. **Upflow Anaerobic Sludge Blanket Reactors** (UASB), **Induced Sludge Blanket Reactors** (IBR) and **Anaerobic Sequencing Batch Reactors** (ASBR), are digesters that use the settling characteristics of sludge solids to keep microorganisms in the reactor.

Anaerobic Membrane Bioreactors are similar to fixed filmed reactors in that biofilm is cultivated on thin sheets of textile. High strength organic liquids pass through the membrane under pressure where they are converted to biogas. Pieces of fabric are also added to UASB reactors to increase biogas production. These digesters are called **Suspended Particle Attached Growth Reactors.**

Solid State Anaerobic Digestion is a process in which solids degradation is performed on solid, stackable material in a separate reactor prior to methane conversion. This is an emerging technology that could potentially make wide-spread use of manure in the co-digestion of lignocellulosic materials.

Types of Manure Used

The most common types of digesters used in the Chesapeake Bay Watershed are complete mix reactors for dairy manure slurry, plug flow and mixed plug flow for semi-solid dairy manure, and covered lagoon digesters for low-solids slurry swine and dairy manure.

Transfer Efficiencies of Anaerobic Digestion

Anaerobic digesters are normally placed immediately after animal confinement -- to receive the freshest substrate possible. Anaerobic digestion may be preceded by a pretreatment system to alter fresh manure to make it more useable in the digester. The two most common pretreatment schemes are settling to concentrate substrate, and mechanical solid-liquid separation to remove suspended solids from liquid influent. Co-digestion substrates may be added to influent to increase biogas production.

A black box diagram for anaerobic digestion is shown in Figure AD.6. The box represents a complete mix digester, a plug flow digester, a mixed-plug flow digester, or the first cell of a covered lagoon digester.

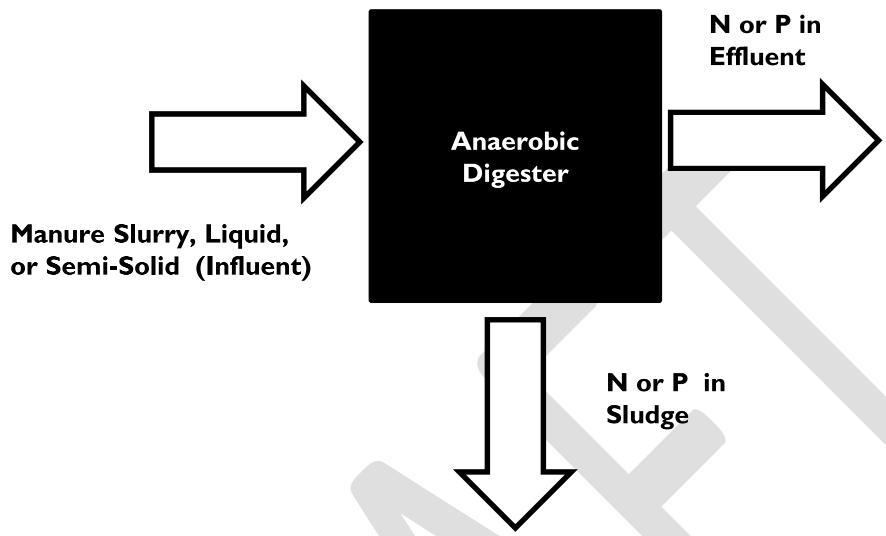

Figure AD6. Anaerobic Digestion Black Box Process

Biogas contains only trace amounts of nitrogen, so nitrogen transfer by volatilization are insignificant for all types of anaerobic digesters.

Sludge is mixed with liquid effluent in complete mix digester; therefore, nutrients are not separated from the main manure flow. Likewise, the nutrients in the semi-solid effluent of plug flow and mixed plug flow digester are not separated from the main manure stream. Sludge settles to the bottom of the first cell of covered lagoon digesters. It may remain captured in the first cell for up to 20 years, and once removed; lagoon sludge is often sold and spread away from the original farm.

If sludge is stored in a covered lagoon for greater than 10 years, separation efficiencies can be calculated using Equations AD.1 and AD.2.

$$NSE = \frac{(\text{Mass of TN in Sludge})}{(\text{Mass of TN in Influent})} \times 100 \qquad \text{AD.1}$$

$$PSE = \frac{(\text{Mass of TP in Sludge})}{(\text{Mass of TP in Influent})} \times 100 \qquad \text{AD.2}$$

Default Transfer Efficiencies for Anaerobic Digestion

Without detailed knowledge of the process factors for anaerobic digester, the default Nitrogen Volatilization Efficiencies (NVE), Nitrogen Separation Efficiencies (NSE) and Phosphorus Separation Efficiencies (PSE) are zero (0).

If the sludge storage time of a covered lagoon digester exceeds 10 years, the transfer efficiencies given in Table AD.3 may be used for input into the Chesapeake Bay Model.

Review of Available Science on Anaerobic Digestion

Anaerobic digestion is the biological decomposition of organic matter in the absence of oxygen. The main effect of anaerobic digestion is to convert organic carbon to biogas. The conversion process takes place in a number of biologically activated steps (Figure AD.7), with each step requiring a separate community of microorganisms. The relationship is symbiotic, in that each community completes a separate step in digestion. Each community produces its own waste, and the waste of one is the food of another. Anaerobic digestion involves two to four steps, depending on where you draw lines in the process (Figure AD.7). Communities of hydrolytic bacteria (sometimes called liquefiers) break complex organic matter (OM) down into simpler compounds. Acid forming bacteria (acidifiers) convert the simple compounds to volatile fatty acids (VFA) – principally acetic acid (vinegar). Hydrolysis (liquid formation) and acidosis (acid formation) are commonly lumped together and called anaerobic fermentation. Some microbiologists also distinguish between formation of mixed volatile fatty acids (acidosis) and the creation of acetic acid (acetogenesis). Methanogens are methane forming microorganisms belonging to the Archaea domain -- very simple, single-cell organisms similar to bacteria. Methanogens take the end products of anaerobic fermentation – VFA, H_2, CO_2, and H_2O – and use them to form methane. Other byproducts of methanogenesis include Ammonium (NH_4^{+1}) and Sulfide (S^{-1}) ions.

Key Process Factors

Hydraulic Retention Time (HRT) is the average time liquid remains in an anaerobic digester. Anaerobic digestion commonly takes place in a continuous flow reactor. If the working volume of the reactor does not change, and the volume entering the reactor (influent) equals the volume leaving (effluent), HRT is calculated by dividing the reactor working volume by the effluent flow rate.

Cell Retention Time is calculated by dividing the mass of microorganisms residing in the reactor by the mass of organisms leaving the reactor. If cell retention time is greater than the time required for microbes to reproduce, the microbial population remains stable. If cell retention time is shorter than the reproduction time, a new cell will not replace one leaving the reactor, and the population declines, or "washes out".

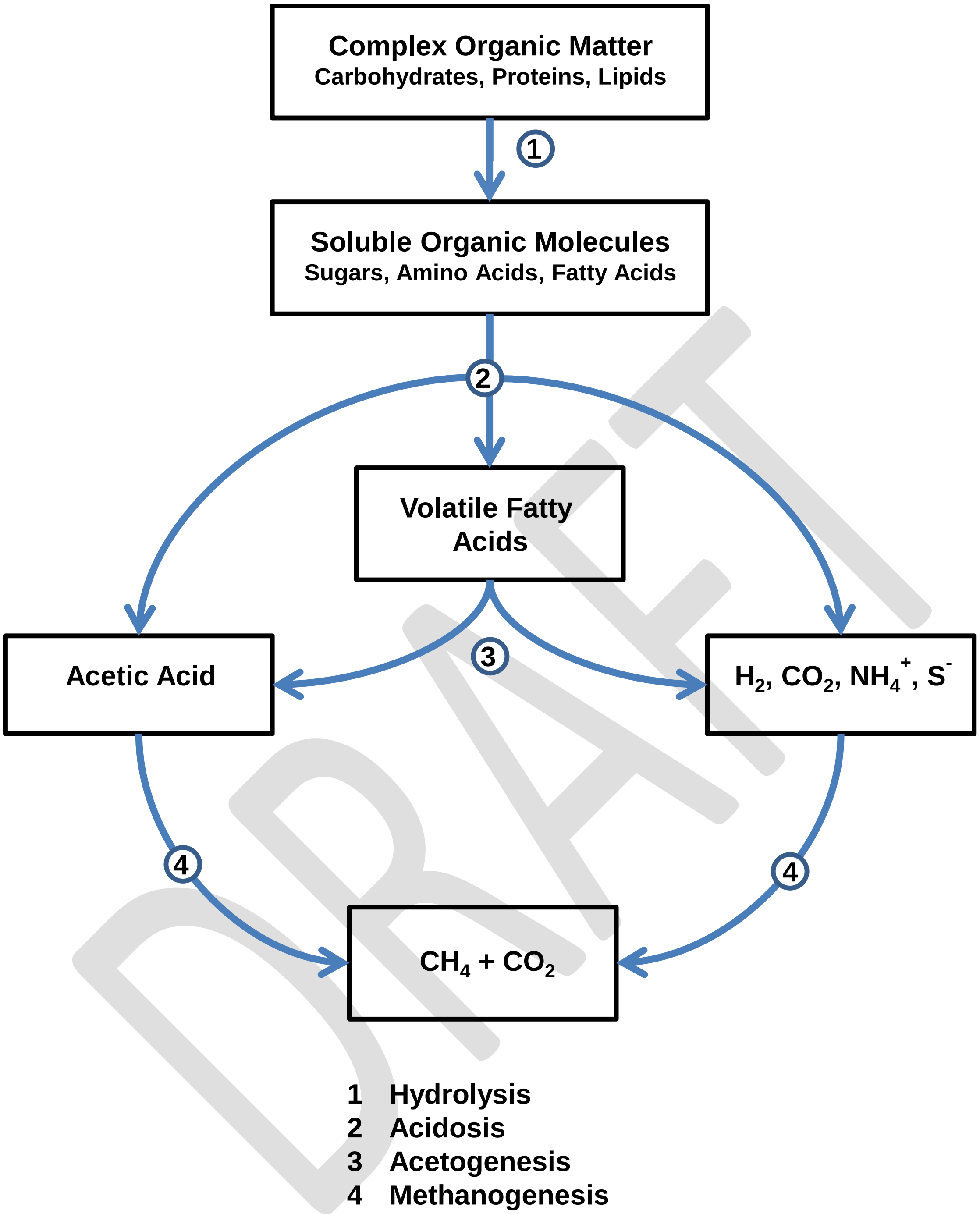

Figure AD.7. Conversion of Organic Matter to Biogas through Anaerobic Digestion (from Hamilton, 2014a).

Solids Retention Time (SRT) is often substituted for cell retention time, because it is easier to measure the total mass of solid particles than the mass of living organisms in a reactor. Solids retention time is calculated by dividing the mass of solids in the reactor by the mass of solids leaving the reactor.

Food to Mass Ratio (F:M) is the ratio of digestible substrate fed to a digester to the mass of active biomass in the reactor. Food to mass ratio defines where microbial communities are situated on the generalized microbial growth curve.

Organic Loading Rate (OLR) is the mass of organic matter fed to a digester divided by the volume of the reactor. Organic loading rate approximates F:M but does not require knowing the mass of microorganism retained in the reactor.

Operating Temperature determines the species of microorganisms inhabiting the reactor. Digesters are divided into four categories based on temperature: thermophilic (those operating at temperatures greater than 122°F (50°C), mesophilic (those operating close to 95°F-35°C), cryophilic (operating at temperatures lower than 95°F-35°C), and ambient (those that follow the naturally occurring temperature).

Optimum operating conditions for types of anaerobic digesters covered in this report are given in Table AD.1.

Table AD.1: Optimum Operating Conditions for Single-Stage Anaerobic Digesters based on Type of Reactor and Temperature Regime of Microflora.

	Complete Mix and Plug Flow		Covered Lagoon
	Thermophilic	**Mesophilic**	
Operating Temp (°F)	125-135	85-100	Variable
Solids Retention Time (days)	10-15	20-30	>60
Organic Loading Rate (lbs VS 1000 ft^{-3} day^{-1})	60-400	50-300	9[1]

[1]based on climatic conditions existing in the Central Chesapeake Bay (NRCS, 2003).

Key Measures of Digester Performance

Organic Matter Removal Efficiency (OMRE) measures how thoroughly a reactor digests substrates through anaerobic fermentation. Organic Removal Efficiency is calculated by subtracting the mass of organic matter leaving the digester from the mass of organic matter entering the digester and dividing by the mass of organic matter entering the digester. Either Volatile Solids (VS) or Chemical Oxygen Demand (COD) can be used to measure organic matter. Organic matter removal efficiency is the chief parameter used to measure the ability of digesters to reduce the pollutant strength of influent.

Methane Yield (MY) is calculated by dividing the volume of CH_4 gas produced over a given time period (usually one day) by the mass of OM added to the reactor over the same time period. Organic matter can be measured as either VS or COD; but, depending on the analysis method used, MY may have a slightly different meaning. Two factors affect the percentage of CH_4 in biogas: substrate digestibility and F:M. As digestibility increases and F:M decreases, the percentage of CH_4 in biogas increases.

Volumetric Reactor Efficiency (VRE) is calculated by dividing the daily CH_4 production rate by the volume of reactor. Volumetric reactor efficiency is a rough measure of the net energy production of a digester. If VRE is high, it is unlikely that "parasitic" loads (energy that is diverted to operate the digester -- to mix or heat the reactor, for example) will be greater than the energy output of the digester. It is important to report only the volume of CH_4 produced when calculating VRE, because the other gaseous components of biogas have little heating value.

Removal of Organic Matter

The highest expected OMRE for manure digested by the digestion systems covered in the report is 60%. Actual VS removal is heavily dependent on OLR as shown in Figure AD.8.

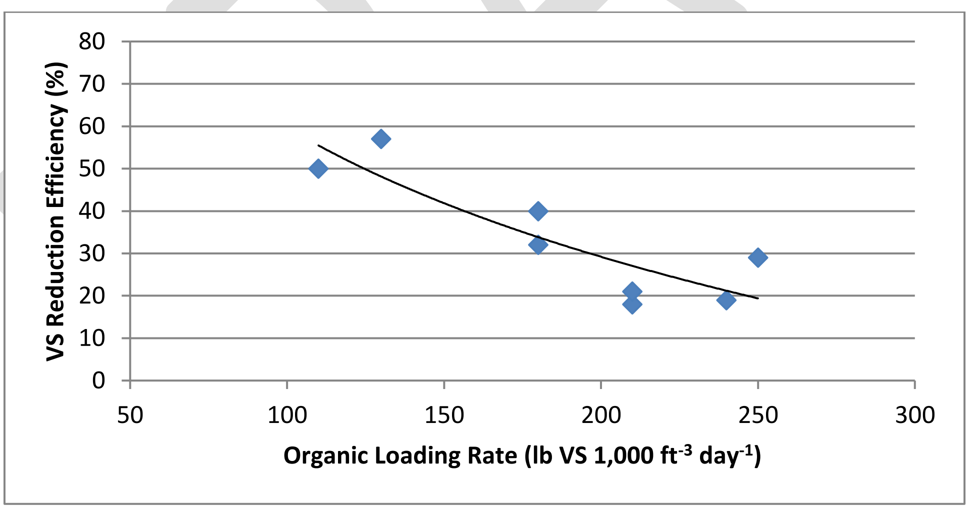

Figure AD.8. Effect of OLR on OMRE for Farm-scale, Mesophilic, Single Cell Cattle and Swine Manure Digesters (from Camarillo et al., 2013; Gooch and Labatut, 2014; Gooch and Pronto, 2008; Pronto and Gooch, 2008a; Pronto and Gooch, 2009; Schievano et al., 2011; Shayya, 2008).

Given the dependence of organic matter removal on loading rate, the VS removal efficiency of the digesters covered in this report can be estimated to be those tabulated in Table AD.2.

Table AD.2. Values for Volatile Solids Removal Efficiencies based on Digester Type, Operating Temperature, Retention Time, and Organic Loading Rate.

Type of Digester	Operating Temp (°F)	Minimum HRT (days)	OLR (lbs VS 1000 ft^{-3} day^{-1})	VS Removal Efficiency (%)
Plug Flow **Mixed Plug Flow** **Complete Mix**	90-105	20	<100 100-250 >250	50 40 20
Plug Flow **Mixed Plug Flow** **Complete Mix**	130-140	10	<150 150-350 >350	50 40 30
Covered Lagoon		HRT ≥ Value Given in Figure AD.9	OLR ≤ Value Given in Figure AD.10	50

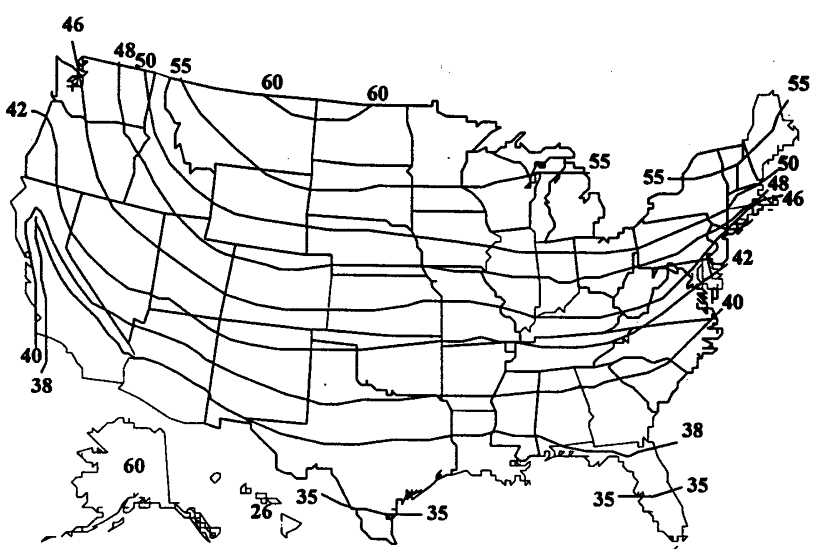

Figure AD.9. Minimum Hydraulic Retention Time (days) for Covered Lagoon Digesters (From NRCS , 2003)

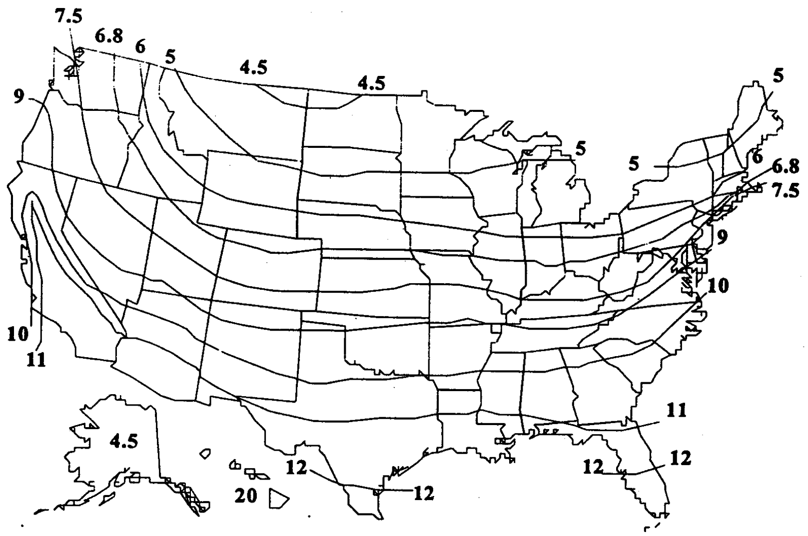

Figure AD.10. Maximum Organic Loading Rate (lbs VS 1000 ft^{-3} day^{-1}) for Covered Lagoon Digesters (From NRCS, 2003)

With properly designed and operated digesters, it is expected that organic matter will be completely digested to biogas, but in many cases – especially in overloaded digesters – organic matter may be converted to volatile fatty acids, with only a small portion becoming biogas. This incomplete digestion may actually increase the pollutant strength of manure, due to the high oxygen demand of volatile organic acids. Alburquerque, et al. (2011) showed that land application of effluent from heavily loaded, out-of-balance digesters leads to nitrogen immobilization in soil. The undigested organic carbon in the effluent, combined with low soluble nitrogen content, results in increased growth of microorganisms in the soil and removal of soil nitrogen.

Nutrient Transformations

Anaerobic digestion does not alter the **Total Nitrogen (TN)** content of manure. A common feature of digestion; however, is conversion of protein and urea nitrogen to inorganic nitrogen (Field, et al., 1984). Inorganic nitrogen in digesters exists in two forms Ammonia Gas (NH_3) and Ammonium Ion (NH_4^+). Both forms are in equilibrium due to auto dissociation of NH_3 with water, which is highly dependent on pH. **Total Ammonia Nitrogen** (TAN) is the concentration of nitrogen held in both NH_4^+ ions and dissolved NH_3 gas, and is sometimes abbreviated as NH_4+NH_3-N. The increase in TAN during digestion is typically 20% to 30%; however, increases greater than 50% are not unusual (Lansing, et al., 2010). Transformation of Org-N to TAN appears to be a function of digester OLR (Figure AD.11). At lower loading rates, inorganic nitrogen may be more likely to be reabsorbed into microbial biomass.

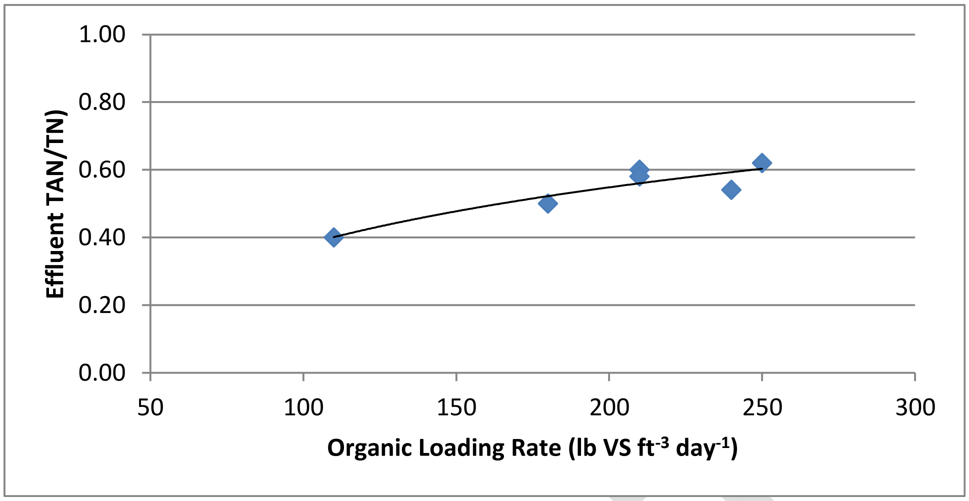

Figure AD.11. Effect of Organic Loading Rate on Concentration of Total Ammonia Nitrogen (TAN) in Effluent of Farm-Scale, Mesophilic, Single Cell, Cattle and Swine Manure Digesters (from Camarillo et al., 2013; Gooch and Labatut, 2014; Gooch and Pronto, 2008; Pronto and Gooch, 2008a; Pronto and Gooch, 2009; Schievano et al., 2011; Shayya, 2008).

Most reported losses of TN in anaerobic digesters are the result of solids accumulating in the digester. Some of the TN reduction may also be the result of ammonia volatility and subsequent loss of TAN from digester effluent. During land application, it is expected that ammonia losses will be greater in surface applied digester effluent compared to raw or stored manure. But, if incorporated or injected into the soil, digester effluent may increase crop production due to the more readily available TAN.

Due to the higher solubility of TAN compared to Organic N (Org-N), most of the nitrogen contained in a digester will remain in the liquid rather than solid portion. Camarillo, et al. (2012) found that 70% of TN entering a digester left the system in liquid portion of digester effluent. Beegle and Moncagave (2014) found similar ratios of TAN to TN in both digester influent and effluent, but since the mass of liquids is greater than the mass of solid leaving a solid-liquid separator, the greatest mass of nitrogen remains in the liquid stream.

Anaerobic digestion does not alter the **Total Phosphorus** (TP) content of manure. Most reported losses of total P in digesters are related to solids accumulation in the reactor. Anaerobic digestion, however, does convert organic phosphorus (Org-P) to phosphate (PO_4^+) phosphorus (Field, et al., 1984). Typically, the increase in phosphate P between digester influent and effluent is in the order of 10 to 30%. Conversion of Org-P to Phosphate does not appear to be as dependent on OLR as conversion of Org-N to TAN.

Although there is a trend towards conversion to inorganic forms of phosphorus, this does not mean that effluent phosphate is water soluble. Based on chemical equilibrium modelling, Wahal, et al. (2010) showed most of the P in the effluent of digesters treating dairy manure was precipitated as insoluble Ca and Mg salts. Field, et al. (1984) found that 60% of effluent P was associated with solids in digesters treating both cattle and swine manure. Beegle and Moncagave (2014) found that 30% of total phosphorus was present in the liquid portion of digester effluents, and 70% was in the sludge portion.

Settling will increase the amount of TP transported in the higher solids stream leaving a settling tank or clarifier. Using a mechanical solid-liquid separator may not be as effective as settling to concentrate TP, since separation efficiency is highly dependent on screen size. Digested solids and crystalline precipitants tend to be smaller than their undigested counterparts, and may pass through solid-liquid separator screens.

Defined Transfer Efficiencies Based on Process Factors.

If the type of digester and sludge storage capacity of covered lagoon digesters is known, the transfer efficiencies given in Table AD.3. may be used for input to the Chesapeake Bay Model.

Table AD.3. Defined Transfer Efficiencies for Anaerobic Digestion for All Types of Manure.

Type of Digester	Transfer Efficiency (%) NVE	NSE	PSE
Plug Flow and Mixed Plug Flow	0	0	0
Complete Mix	0	0	0
Covered Lagoon with Sludge Storage Exceeding 10 Years	0	30	60

Ancillary Benefits of Anaerobic Digestion

Energy Production

In agriculture, production of energy is generally the primary use of anaerobic digester, and solids reduction is an ancillary effect. Methane gas is flammable, with an energy content of 1,000 btu ft^{-3} (37 MJ m^{-3}). Because biogas is composed of 40 to 70% CH_4, energy content of biogas lies in the range 400 to 700 btu ft^{-3} (19 to 26 MJ m^{-3}). Efficiency of the anaerobic digestion process is measured in methane yield. Biological efficiency of an individual digester is measured as volumetric reactor efficiency. The energy efficiency of a digester system is measured by the net energy production of the system (Energy produced through conversion of biogas minus energy used in heating, mixing, and converting biogas energy to a useable form). Methods to convert the potential energy of CH_4 to useable energy are direct combustion of biogas, combined heat and power systems using internal combustion or fuel cell technology, upgrading biogas to pipeline quality natural gas, using cleaned biogas in compressed natural gas vehicles, and injection of biogas into diesel engines. Major issues with use of biogas in engines and fuel cells are H_2O, CO_2, and H_2S content.

Waste Stabilization and Odor Reduction

Anaerobically treated manure is less odorous, less putrescible, and has a lower ~~a~~ C:N than raw manure. Level of stabilization is directly related to removal of oxygen demand, which is ~~realted~~related to, but generally greater than VS reduction. Chemical Oxygen Demand (COD) removal efficiency of mesophilic digesters treating swine manure is in the range of 60 to 80% (Boopathy, 1998; Andara & Esteban1999). As with VS reduction, COD reduction is dependent upon the completeness of the anaerobic digestion process and is, therefore, impacted by HRT and OLR.

Green House Gas Emission Reduction

Fugitive release of CH_4 during manure storage, handling, and land application may contribute to climate change. Anaerobic digestion reduces these fugitive sources by stabilizing manure organic matter in a sealed vessel. Provided captured CH_4 is converted to CO_2 through combustion or use a fuel as described above before release into the atmosphere, anaerobic digestion reduces greenhouse gas potential because CO_2 has a much lower heat trapping potential than CH_4. Though CH_4 has a short lifespan in the atmosphere (12 years), on a pound-for-pound basis its heat trapping potential is 28-36 times greater than CO_2 over a 100 year period (US EPA 2015).

Pathogen Reduction

Anaerobic digestion effectively inactivate intestinal pathogens (Hashimoto 1983), and may destroy viruses given sufficiently long HRT (Salminen & Rintala 2002). Destruction of manure pathogens is more effective at thermophilic than at mesophilic temperatures (Shih 1987; Bendixen 1994); However, even cryophilic systems (20 °C for 20 days) can significantly reduce total coliforms (97.94-100%), *E.coli* (99.67-100%) and indigenous strains of *Salmonella*, *Cryptosporidium* and *Giardia* (Côté *et al.* 2006). Besides temperature, the destruction of pathogens in anaerobic treatment systems is dependent upon HRT, with longer retention time yielding greater bacterial and viral destruction (Kun *et al.* 1989).

Land Application

During land application it is expected that TAN losses will be greater in surface applied digester effluent compared to raw or stored manure. But, if incorporated or injected into the soil, digester effluent may increase crop production due to the more readily available TAN. The positively charged NH_4^+ is more likely to be held in soil by negatively charged soil particles than other forms of nitrogen, such as nitrate (NO_3^-). Because of this change in nitrogen distribution, applying digested swine manure in place of undigested swine manure reduced nitrogen leakage to the environment by about 20% (Blomqvist, 1993; Berglund & Börjesson, 2006). Add to this the benefits of pathogen removal and odor control, land application of digester sludge and effluent stands to increase the efficiency of nutrient application at reduced environmental impact.

Potential Hazards of Anaerobic Digestion

The greatest environmental risk posed by anaerobic digestion is fugitive release of CH_4 due to leaking digester tanks, piping, etc. If biogas is not flared or used in combustion engines or fuel cells, all the CH_4 produced by digestion is released into the atmosphere.

Anaerobic digestion is a complex mechanical undertaking. Under current economic conditions, anaerobic digestion has not been shown to be economically favorable unless the monetary value of reducing carbon dioxide equivalents is considered. Seeing that little nutrient removal is achieved through digestion, producers must weigh the cost of implementation against energy savings, manure handling improvements, and non-monetary environmental improvement before considering anaerobic digestion.

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7. Settling

Settling, sometime referred to as **Sedimentation**, is the use of gravity to remove suspended solids from a liquid manure stream.

Settling Terminology

Influent is the liquid or slurry flowing into a settling device.

Effluent or Supernatant is the lower Total Solids (TS) liquid flowing out of a settling device.

Sludge is the higher TS material settling at the bottom of a settling device.

Suspended Solids are non-dissolved particles remaining after water is evaporated from a liquid sample. By definition, suspended solids are solid particles that are retained on a 1.5 micron filter (APHA, 2012).

Overflow Velocity is the flow out of a settling device divided by its surface area. It is the effective velocity a particle experiences as it travels the length of the device.

Types of Settling Devices

All settling or sedimentation devices rely on a low overflow velocity for particles to settle. Settling devices are defined by three characteristics, 1) if they are operated continuously or as a batch operation, 2) how sludge is stored in the device, and 3)what type of mechanism is used for effluent to the device.

Clarifiers (Figures STTL.1, STTL.2) are an adaptation of sewage treatment technology. Although rare in manure management, they are none the less, the most efficient devices for sedimentation in terms of size and flow rate. Solids are removed from clarifiers at the rate at which sludge accumulates, thus maintaining a constant sludge volume. The surface area is designed for an overflow rate capable of removing the smallest settable particle existing in the manure stream. Clarifiers are operated on a continuous basis, that is, influent flow is equal to effluent flow and influent is constantly added to the clarifier. Clarifiers are very effective at concentrating solids into sludge streams for further processing. For this reason, they are sometimes called **Sludge Thickeners**.

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Figure STTL.1. Rectangular Clarifier (Wikipedia.org)

Figure STTL.2. Circular Clarifier (copyright Monroe Environmental Corp, Monroe, MI; from, Encyclopedia of Chemical Engineering Equipment : umich.edu)

Settling Basins are batch settling devices. Accumulated solids are stored in place. Once the basin is filled with solids, slurry is directed to another settling basin. Settled sludge is allowed to further dewater and dry in the basin. Two types of overflow mechanisms are used in settling basins: Flashboards and Porous Dams. **Flashboards** (Figure STTL.3) are used to sequentially raise and lower the basin's liquid level. As solids accumulate, boards are added to keep the clarifying layer above sludge storage. Once the basin is filled with solids, boards are removed to dewater the accumulated sludge. **Porous Dam** basins are operated without liquid level control. Manure enters the basin and solids are trapped by bridging behind a slatted wall (Figure STTL.4). Porous dams are sometimes called **Weeping Walls** because liquids continuously ooze out of the solids accumulated behind the dam. Regardless of overflow mechanism, sludge is removed from the settling basin using a tractor and front end loader after sludge dewatering (Figure STTL.5).

Figure STTL.3. Flashboard Dam Dewatering Device (forums.pondboss.com)

Figure STTL.4. Porous Dam Dewatering Device (Iowa State Extension).

Figure STTL.5. Weeping Wall Storage Basin on a Large Dairy Farm in Erath County, Texas The Porous Dam has been Opened for Sludge Removal (YouTube:OSUWasteManagement).

Settling Devices not Covered in This Report

Settling basins used to remove sand bedding from dairy manure are not covered in this report. The settled sand is recycled to animal housing for bedding. Any nutrients adhering to the sand is not removed from the system.

Weeping walls systems designed to contain manure greater than 10% TS do not use settling to separate solids, but rather contain semisolid manure in a dry, uncovered area. They are considered storage, not treatment in context of this report.

Types of Manure Used

Any type of animal facility that uses flushing to remove manure from is a candidate for solid-liquid separation by settling. Gravity settling works well for primary treatment of manure flushed from dairy or swine facilities, milking center wastewater, or runoff from outside loafing areas.

Transfer Efficiencies of Settling Devices

Mechanical Solid-Liquid Separators are normally placed immediately after animal confinement. Chemicals are sometimes added to the manure upstream of the settling device to enhance solids recovery. Chemical enhancement of settling is covered in the Wet Chemical Treatment chapter of this report. Screw or belt presses are often used to increase the solids concentration of settled sludge in clarifiers.

Settling is shown as a black box process in Figure STTI.6. Due to the short time manure slurries stay in a settling device, very little nitrogen is volatilized. The main purpose of settling devices is to separate the manure stream into two waste streams. Often the low solids effluent stream is recycled to remove manure from confinement buildings. Nutrients in both the effluent and sludge streams are utilized in land application; however the smaller volume and mass of the sludge stream allows it to be transported more economically over great distances, making sludge more likely to be utilized off-farm.

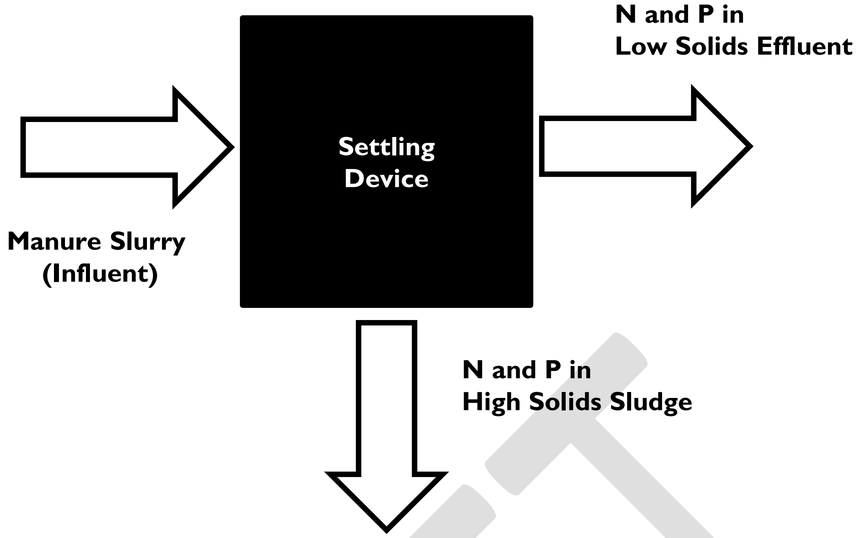

Figure STTL.6 . Settling as a Black Box.

Since settling devices do not remove Nitrogen through volatilization, NVE of settling devices is always zero. Nitrogen and phosphorus separation efficiencies as calculated as shown in Equations STTL.1 and STTl.2

$$\mathbf{NSE} = \frac{\text{(Mass of TN in Sludge)}}{\text{(Mass TN in Influent Slurry)}} \times 100 \qquad \textbf{Equation STTL.1}$$

$$\mathbf{PSE} = \frac{\text{(Mass of TP in Sludge)}}{\text{(Mass TN in Influent Slurry)}} \times 100 \qquad \textbf{Equation STTL.2}$$

Default Transfer Efficiencies for Settling

Without detailed knowledge of the process factors for a particular treatment system, the default Nitrogen Volatilization Efficiencies (NVE), Nitrogen Separation Efficiencies (NSE) and Phosphorus Separation Efficiencies (PSE)in Tables STTL.1 should be used in the Chesapeake Bay Model. If type of settling device type of manure, and TS content of influent manure slurry are known, the defined values shown in Table STTL.5 may be used.

Table STTL1. Default Transfer Efficiencies of Gravity Settling based on Type of Influent.

Type of Influent	Transfer Efficiency (%)		
	NVE	NSE	PSE
Milking Center Wash Water	0	20	47
Flushed Dairy Manure	0	25	45
Flushed Swine Manure	0	20	50

Review of Available Science on Settling

Gravity settling of suspended solids is an effective method of solid-liquid separation for manure slurries with solids content less than 3% TS. Solid-liquid separation by gravity can be achieved using a large variation of designs; however, they can generally be divided into two types: clarifiers, which operate on a continuous basis and store sludge for a relatively short period of time; and basins which settle solids in batches and store sludge for periods ranging from a few days to several months (Worley and Das, 2000). Provided that solids build-up is not excessive, the performance of the two types is similar. Basins designed with porous outlets to allow dairy manure solids to drain are called weeping wall basins (Muktar et al., 2011; and Meyer et al., 2004). Sometimes weeping walls are used to store and dewater semi-solid manure.

The main requirements for gravity solid-liquid separation are: 1) flow velocities low enough to allow solids to settle (less than 0.5 ft/sec), 2) a detention time sufficient to allow capture of the settling solids (generally 20 minutes or longer), and 3) sufficient solids storage below the settling zone to maintain settling efficiency.

Mass versus Concentration Efficiency

The mass flows for a gravity settling basin are shown in Figure STTL7. The volumes shown in the diagram correspond to the time period of interest. For example, the volume loaded into the basin would be the average influent flow rate (Q_{IN}) multiplied by the total time influent flowed into the basin. In most cases, information is gathered to determine the total volume loaded per day. The volume of manure to be removed is the sum of total volume of settled material that will accumulate over the defined time period and the volume of supernatant that will not be removed in the outfall (Q_{OUT}). The volume of settled solids to be removed at planned time intervals is termed the storage volume, V_{SM}.

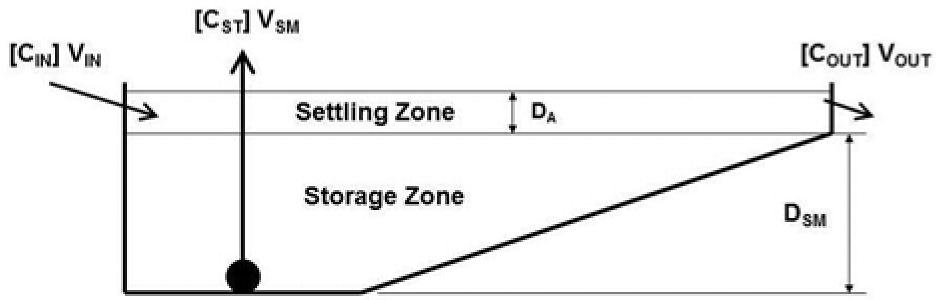

Figure STTL.7. Mass flows for a settling basin.

Where,

$[C_{IN}]$ = concentration of a manure component in the influent liquid manure (),
V_{IN} = $Q_{IN}\,\Delta t$ = volume of wastewater treated over time period Δt (L),
[Ceff] = concentration of a manure component in the outfall (g/L),
Veff = $Q_{OUT}\,\Delta t$ = volume of treated liquid that flows out of the basin (L),
$[C_{ST}]$ = concentration of a manure component in the storage volume (g/L), and
V_{SM} = volume of settled material that accumulates over Δt (L).

Applying of the law of conservation of mass to the basin shown in Figure STTL7 gives:

$$C_{IN}\,V_{IN} = C_{eff}\,V_{eff} + C_{ST}\,V_{SM}. \qquad \text{STTL.3}$$

The relationship for the mass ~~removal~~ separation efficiency for a settling basin can be written as:

$$MRE = 100 \times (C_{IN}\,V_{IN} - C_{eff}\,V_{eff}) / C_{IN}\,V_{IN} \qquad \text{STTL.4}$$

Concentration ~~removal~~ separation efficiency, which is what farmers sometimes measure by taking grab samples of influent and effluent, is defined as:

$$CRE = 100 \times (Cin - Ceff)/\,Cin \qquad \text{STTL.5}$$

Concentration ~~removal~~ separtation efficiency is not equivalent to mass ~~removal~~ separtion. Some volume will always be stored as sludge. If sludge solids concentration is low, the difference between mass and concentration ~~removal~~ separation can be substantial. Therefore, ~~removal~~ separation efficiency should always be measured as mass ~~removal~~separation. Measuring flow into and out of a settling device is critically important in analyzing their performance.

Measured Performance of Settling Basins

The solids, nitrogen, and phosphorous ~~removal~~ separation measured for gravity settling of dairy and swine manure is summarized in Tables STTL.2, STTL.3 and STTL.4. Gravity settling does not change the concentration of soluble plant nutrients, such as TAN or nitrate, since only solid particles are removed from the liquid fraction that flows through the settler. The amount of soluble nutrients removed is a function of the amount of liquid removed with the settled solids. In general, gravity settling provides higher separation efficiencies than mechanical solid-liquid separation. However, the separated solids generally have higher moisture content and require more space for storage, and must be handled as a slurry or semi-solid.

STTL.2. Summary of Separation Efficiency Data for Gravity Settling of Dairy Manure (Barrow, et al., 1997; Sherman et al., 2000; Chastain, et al., 2001; Converse and Karthikeyan, 2004; Chastain et al., 2005; Hjorth, 2010; Chastain, 2011).

Manure Description	Settling Time (hr)	Influent TS (%)	Separation Efficiency (%)				Settled Volume Fraction
			TS	VS	TN	TP	
Milking Center Wastewater	1.0	0.7	41	47	21	48	0.093
Milking Center Wastewater	1.0	1.7	61	66	41	45	0.254
Dairy manure	0.33	1.0	28	---	17	63	0.165
Dairy manure	0.33	1.0	63	---	22	60	NA
Dairy manure	0.5	4.2	98	98	96	96	0.95
Dairy manure	1.0	4.2	96	96	92	94	0.90
Dairy manure	4.0	1.3	52	---	35	42	0.25
Dairy manure	24	2.5	42	---	33	46	0.25
Dairy manure	1200	3.2	55	---	35	70	0.25

Table STTL.3. Performance of Weeping Wall Basins to Separate Dairy Manure (from Meyers et al., 2004 and Mukhtar et al., 2011).

Locatio n	Description	Influent TS (%wb)	Separation Efficiency %			
			TS	VS	TN	TP
California	Single Basin	1.14 to 1.76	48 – 60	46 – 60	NA	NA
Texas	First Basin in Two-Basin Series	3	67	67	60	55
Texas	Combined Two-Series Basin	3	88	89	84	86

Table STTL.4. Summary of separation efficiency data for gravity settling of liquid swine manure (from Vanotti and Hunt, 1999; Worley and Das, 2000. Powers and Flatow, 2002; Chastain and Vanotti, 2003;).

Manure Description	Settling Time (hr)	Influent TS (%)	Separation Efficiency (%)				Settled Volume Fraction
			TS	VS	TN	TP	
Growing pigs	0.2	0.24	51	NA		17	0.06
Nursery Pigs	NA	0.18	0.02	NA	3.0	23	0.0002
Flushed swine	1.0	0.5	37	46	23	50	0.08
Flushed swine	1.0	1.0	51	56	30	66	0.13
Gravity Settling Pond	NA	1.5	60	---	20	38	NA
Flushed swine	1.0	2.0	68	70	46	81	0.31

Defined Transfer Efficiencies Based on Process Factors

If the type and solids content of manure is known, the values for TN and TP mass ~~removal~~ separation efficiency can be used in the Chesapeake Bay Model for the type of settling device as indicated in Table STLL.5.

Table STTL.5. Defined Transfer Efficiencies of Settling Devices based on Type of Device, Type of Manure, and Manure TS Content.

Type of Device	Type of Manure	Manure TS (% wb)	Transfer Efficiency (%)		
			NVE	NSE	PSE
Clarifier	Dairy, Dairy Milking Center Swine	<3%	0	20	50
Basin	Dairy	<5%	0	35	45
Basin	Dairy Milking Center	<2%	0	20	48
Basin	Swine	<3%	0	30	60
Weeping Wall Basin	Dairy	3 to 10%	0	60	55

Ancillary Benefits of Settling

Settling does not remove nutrients from the manure stream. The stream is essentially divided into two streams one with solids higher than the original manure and one with solids content lower than the original manure. Roughly 20 to 30 % of the manure nitrogen and 40 to 60% of the manure phosphorus will be contained in the higher solids stream. When farms are fractured and scattered over a large land area, farmers can more efficiently management their manure by spreading high solids manure on more distant fields and irrigating low solids manure on fields closest to the barn.

Potential Hazards of Settling

Settling devices do not pose an inherent environmental hazard. A potential increase in environmental damage may occur if concentrated sludge should leak from a settling device and enter surface water. Storage of sludge in settling basin may also increase the chance that greenhouse gases such as CH_4 and N_2O could form from raw manure.

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8. Mechanical Solid-Liquid Separation

Solid-liquid Separation divides manure slurries into two fractions. The solid fraction, sometimes called cake, is the portion leaving the separator with higher total solids content (TS) than the manure entering. The liquid fraction has lower TS content than the original manure.

Mechanical Solid-Liquid Separation Terminology

Influent is manure slurry entering a mechanical solid-liquid separator.

Effluent or Liquor is lower solids liquid stream leaving a mechanical solid-liquid separator.

Cake is the higher solids stream leaving a mechanical solid-liquid separator.

Types of Solid-Liquid Separators

Stationary Screen Separators are perforated metal plates or mesh screens that trap solid particles too large to pass through openings. Liquids pass through screen separators by gravity alone; hence, these devices are sometimes called **Gravity Screen Separators**. There are two primary types of screen separators: inclined screens and in-channel flighted conveyers. **Inclined Screen Separators** (Figures MSLS.1and MSLS.2) are screens set at an angle, so as Influent is added to the top of the screen, separated solids slide down and thicken at the bottom of the screen. **In-Channel Flighted Conveyor Separators** (Figure MSLS.3) are designed to remove solids from manure flushed into a tank or cross channel. Manure solids are removed from the tank and are carried up an inclined screen by paddles on a continuous chain. Liquids drain back into the tank after being removed from the manure by gravity.

Rotating Screen Separators (Figure MSLS.4) separate solids using a large, porous drum constructed from wedge-wire screen attached to a frame. The drum slowly rotates around its horizontal axis. Manure is distributed evenly on the top of the rotating screen at a rate compatible with the rotational speed of the drum and screen size. Liquids passing through the drum by gravity are collected in a channel below the screen. The separated solids on the outside of the screen are removed by a stationary scraper.

Screw Press Separators (Figure MLSS.5) use a large screw to force manure down a tube and through a cylindrical screen. A plug of manure solids forms at the end of the tube where manure is forced through a small opening. The resulting internal pressure within the tube forces liquids through the screen. The pressure, and flow of separated solids leaving the separator, is controlled by a set of pressure plates. The amount of force exerted by the pressure plates affects the moisture content of the separated solids.

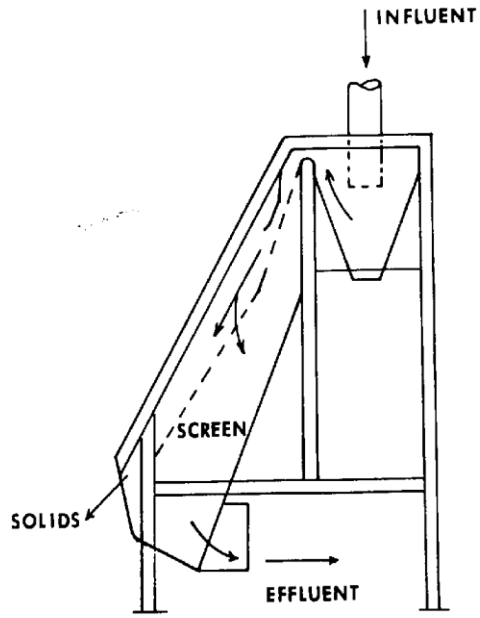

Figure MSLS.1. Inclined Screen Solid-Liquid Separator (from Shutt et al., 1975).

Figure MSLS.2. Dual Inclined Screen Solid Separators in use on a Dairy Farm in Comanche County, Texas (YouTube:OSUWasteManagement).

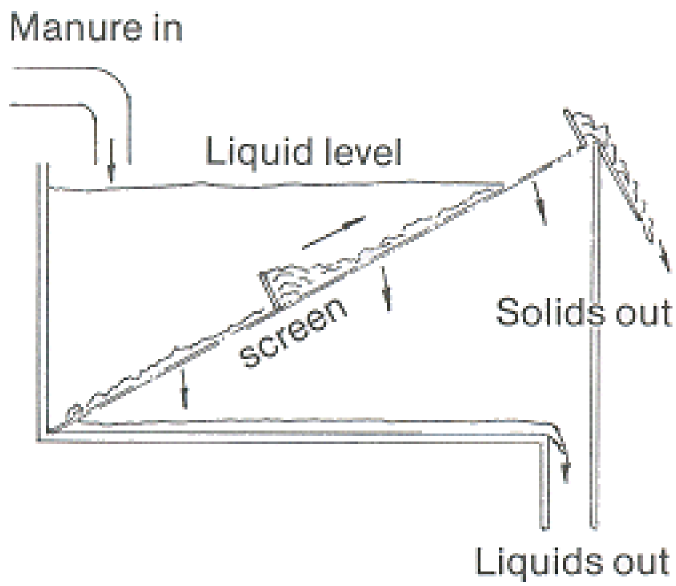

Figure MSLS.3. In-Channel Flighted Conveyor Screen Solid-Liquid Separator (from Fleming, 1986).

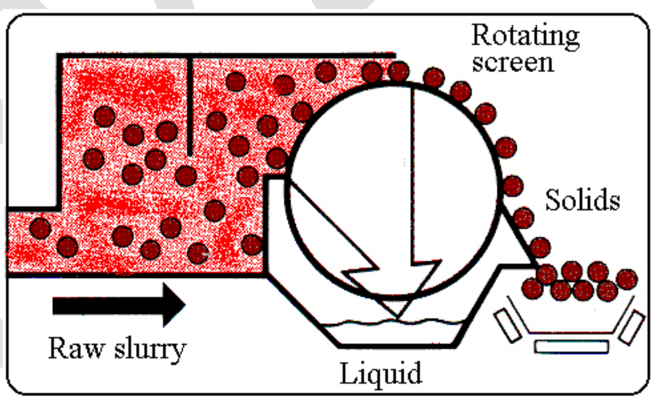

Figure MSLS.4. Rotating Screen Solid-Liquid Separator (from Ford and Fleming, 2002).

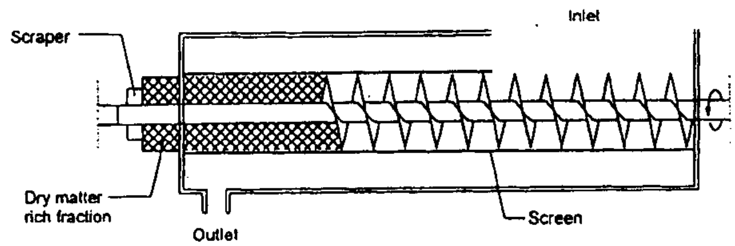

Figure MSLS.5. Screw Press Solid-Liquid Separator (from Møller et al., 2000).

Belt Press Separators (Figure MSLS.6) consist of a flat, fabric belt that runs horizontally between two rollers. Slurry is discharged onto the belt and the rollers squeeze the liquid fraction through the porous belt. The dewatered cake remains on the belt and scrapped off and expelled to a solids collection area. The liquid fraction is collected and transferred to storage or additional treatment.

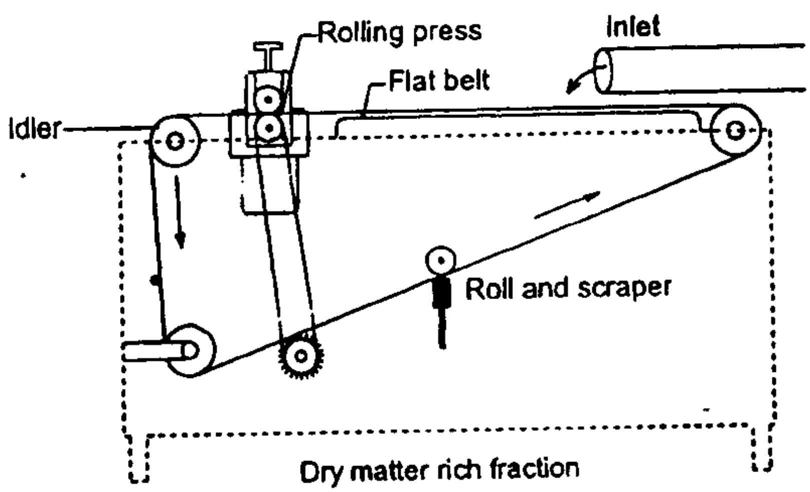

Figure MSLS.6. Belt Press Separator (From Møller et al., 2000).

Brushed Screen Roller Press Separators (Figure MLSS.7) use two concave screens in series to separate manure solids and liquids. Manure is added to the first screen, which is kept clean by rotating brushes moving solids onto the second screen. A roller press squeezes more liquid out of the manure through the second screen. Manure solids are brushed out of the device by brushes attached behind the rollers.

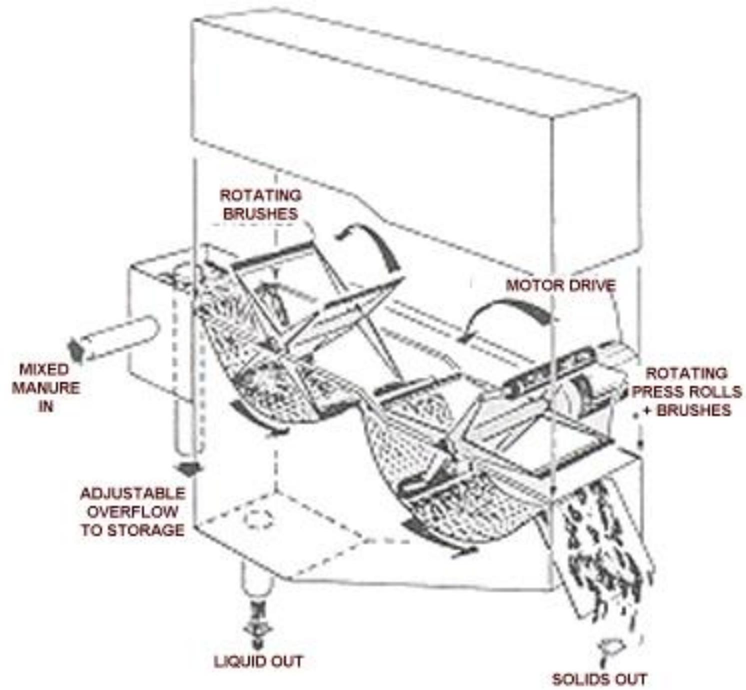

Figure MSLS7 Brushed Screen Roller Press Separator (from Ford and Fleming, 2002).

Centrifuges exploit the difference between particle and liquid density for ~~removal~~ separation of suspended material. Particles are accelerated by rotating the manure about a fixed axis. Particle acceleration is a function of the speed and radius of rotation. A common type of centrifuge used for manure treatment is the **Decanter (or Decanting) Centrifuge** (Figures MSLS.8, MSLS.9). The decanter centrifuge uses an auger turning inside a rotating cylinder. Manure slurry is pumped into centrifuge through the hollow auger axis. Manure exits through holes in the auger and is thrown to the outside of the cylinder by centrifugal force -- separating the manure into a liquid and a solid layer. The auger rotates at a higher speed and in the opposite direction of the cylinder, moving the solid fraction towards the conical end of the cylinder, where it is discharged. A small lip or weir holds liquids in the rotating cylinder. A portion of the separated liquid "decants" over the weir as liquid accumulates in the spinning cylinder.

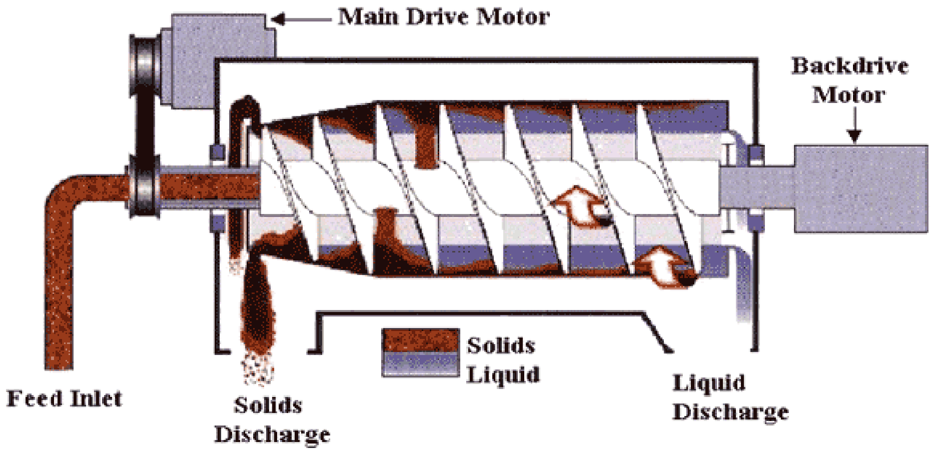

Figure MSLS.8. Decanter Centrifuge (from Hutchinson Hayes Separations Inc., Hutch-Hayes.com).

Figure MSLS.9. Decanter Centrifuge (Green and Silver Device on Trailer) being Demonstrated on a Dairy Farm (GEA.com)

Devices not Covered in This Report

Mechanical devices that separate sand bedding from dairy manure are not covered in this report. The separated sand is recycled to animal housing for bedding. Sand is a nutrient free, inert material which never purposefully leaves the housing area. Any manure nutrients adhering to the sand eventually find their way into the manure stream and are then accounted for as manure the Chesapeake Bay Model.

There are a number of mechanical solid-liquid separators in addition to the six described in detail in this report. They have not been included because of limited on-farm performance data in the literature.

Vibratory Screens are another variation of a stationary screen. Usually, the screen is circular and is oriented horizontally instead of inclined. Solids are moved to the outside of the screen by a combination of vibration and a slight bowing in the screen. Liquids flow through the screen by gravity.

Centrifilters are spinning circular screens or filter cloths. Manure solids are thrown off of the screen by centrifugal force and liquids flow through the screen by gravity. Ridges in the screen help concentrate solids and direct them to the edge of the spinning plate.

Hydrocyclones are cone-shaped separators with no moving parts except for a high-pressure booster pump used to spray manure into the cone. Influent is introduced against the cone wall at the top, wide end at high speed. The strong swirling motion pushes the solids to the outside the cone where they slide down the wall by gravity.

Filter Presses are widely used in the food industry to separate juice from fruit pulps. Plates separated by filter fabric form pockets, which are filled with wet material. The pockets are squeezed in an accordion fashion. Liquids ooze through the filter fabric while solids remain in the pockets.

Transfer Efficiency of Mechanical Solid-Liquid Separation

Mechanical Solid-Liquid Separators are normally placed immediately after animal confinement. The separator may be preceded by a pretreatment system to alter fresh manure to make it more useable. Two common forms of pretreatment are addition of flocculants and thickening by sedimentation to enhance separation.

A black-box schematic of mechanical solid-liquid separation is given in Figure MSLS.10. Solid-Liquid Separators do not remove solids or nutrients from a manure handling system, but rather, separate the manure stream into two waste streams. Nutrients in both streams are utilized in land application. However the the lower weight and smaller volume of the cake makes it more likely to be transported more economically over great distances.

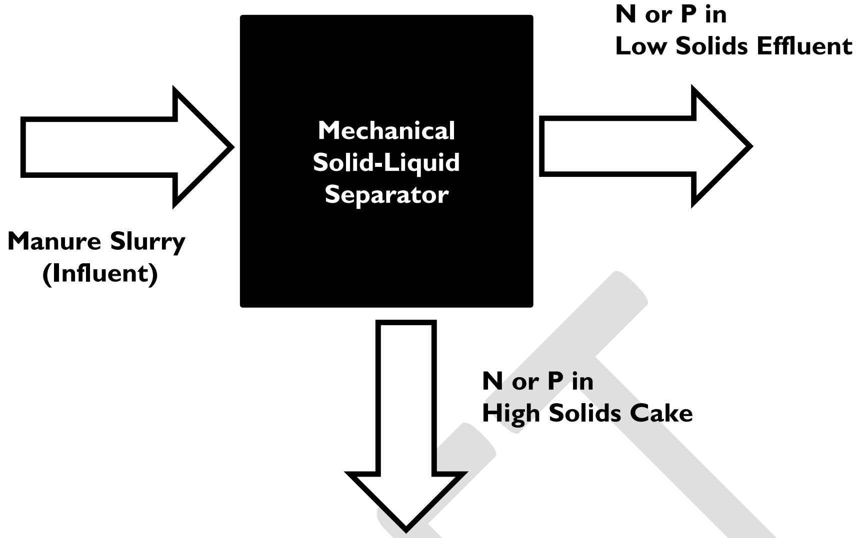

Figure MSLS.10 . Mechanical Solid-Liquid Separation Black Box

Since mechanical solid-liquid separators do not remove nitrogen through volatilization, NVE of mechanical solid-liquid separators is always zero. Nitrogen and phosphorus separation efficiencies as calculated as shown in Equations MSLS.1 and MSLS.2

$$\mathbf{NSE} = \frac{\text{(Mass of TN in Cake)}}{\text{(Mass TN in Influent Slurry)}} \times 100 \qquad \textbf{MSLS.1}$$

$$\mathbf{PSE} = \frac{\text{(Mass of TP in Cake)}}{\text{(Mass TN in Influent Slurry)}} \times 100 \qquad \textbf{MSLS.2}$$

Default Transfer Efficiencies for Mechanical Solid-Liquid Separation

If the type of manure or wastewater treated on a particular farm and the type of mechanical solid-liquid separator used to treat the waste are known, default Nitrogen Volatilization Efficiencies (NVE), Nitrogen Separation Efficiencies (NSE) and Phosphorus Separation Efficiencies (PSE)in Tables MSLS.1 should be used in the Chesapeake Bay Model. If the manure type, influent slurry TS content, and screen or belt opening size of screen and belt separators is known, Tables MSLS.8 through MSLS.10 may be used for input to the Chesapeake Bay Model. If the manure type, influent slurry TS content, and rotational speed of decanting centrifuges are known, Table MSLS.11 may be used for input to the Chesapeake Bay Model.

Table MSLS.1. Default Transfer Efficiencies for Mechanical Solid-Liquid Separators given Types of Separator and Manure.

Type of Separator	Transfer Efficiency (%)				
	NVE	NSE		PSE	
	All Types of Manure	Dairy Manure	Swine Manure	Dairy Manure	Swine Manure
Stationary Screen	0	13	3	11	2
Rotating Screen	0	0	5	0	3
Screw Press	0	8	5	6	8
Belt Press	0	10	10	15	18
Brushed Screen Roller Press	0	13	6	15	6
Centrifuge	0	20	10	45	50

Review of Available Science on Solid-Liquid Separation

Solid-liquid separation divides manure into two fractions. The solid fraction (sometimes called cake) is the portion that has total solids content (TS) greater than the manure entering the device (influent). The liquid fraction (effluent) has a TS content that is less than the manure removed from the facility. Mechanical solid-liquid separators do not alter or transform the nutrients in the manure stream. The sole effect of these devices is to concentrate soluble nutrients such as TAN or water soluble phosphorus in effluent and less soluble nutrients such as organic nitrogen in cake.

Mass versus Concentration ~~Removal~~ Separation Efficiency

A general mass balance for single, mechanical solid-liquid separator is shown in Figure MSLS.11.

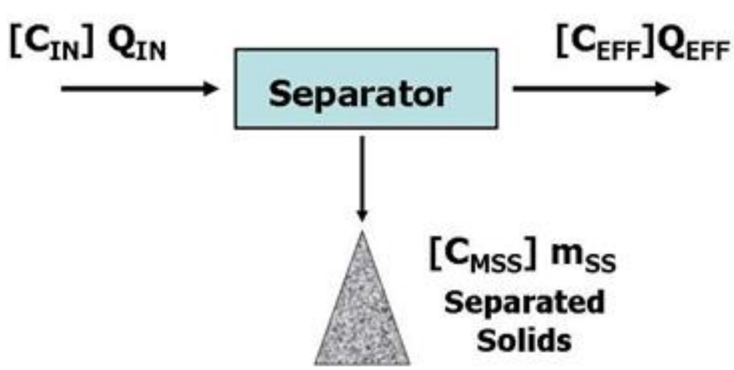

Figure MSLS11. Mass flows for a solid-liquid separator.

Application of the continuity of mass ($m_{IN} = m_{OUT}$) to the situation shown gives:

$$C_{IN} V_{IN} = C_{EFF} V_{EFF} + C_{MSS} m_{SS} \qquad \text{(MSLS.3)}$$

Where,

C_{IN} = Concentration of C in the influent manure (g/L),
V_{IN} = Volume the influent manure (L),
C_{EFF} = Concentration of C in the liquid effluent flowing from the separator (g/L),
V_{EFF} = Volume of the liquid effluent (L),
C_{MSS} = Concentration of C in the separated solids (g / kg),
m_{SS} = Mass of separated solids collected (kg)

The mass ~~removal~~ separation efficiency for a particular component, MRE, can be calculated if at least two of the three masses can be can be determined from data. The three relationships for MRE_C are given below. The equation used to calculate the mass ~~removal~~ separation efficiency depends of the measurements made on the separator.

$$MRE = 100 \times (C_{IN} V_{IN} - C_{EFF} V_{EFF}) / C_{IN} V_{IN} \qquad \text{MSLS.4}$$

$$MRE = 100 \times C_{MSS} m_{SS} / C_{IN} V_{IN} \qquad \text{MSLS.5}$$

$$MRE = 100 \times C_{MSS} m_{SS} / (C_{EFF} V_{EFF} + C_{MSS} m_{SS}) \qquad \text{MSLS.6}$$

Equipment manufactures often report the efficiency of their separators using Concentration ~~Removal~~ Separation Efficiency (CRE) which is calculated by:

$$CRE = 100 \text{ X } (Cin - Ceff)/ Cin \qquad \text{MSLS.7}$$

Concentration ~~removal~~ separation efficiency is not equivalent to mass ~~removal~~ separation efficiency, because the volume of influent (Vin) does not equal the volume of effluent (Veff). Some portion of the influent volume will also exit with cake. If cake is very wet, the differences can be substantial. ~~Removal~~ Separation Efficiency should always be reported on a mass, not a concentration, basis.

Performance of Different Types of Mechanical Solid-Liquid Separators

Stationary Screen: The performance of screen separators is affected by several factors. The most important factors are the screen opening size, TS content of the influent manure, particle size distribution, and the manure flow rate. In general, the highest separation efficiencies have been obtained with manure that has the largest particle sizes (*i.e.* dairy vs swine), smaller screen sizes, and influent manure with a higher TS content. Typically the flow rate of the machine is set by the manufacture to ensure that the screen is not over loaded.

A summary of the available separation data and cake TS content for both inclined screen and in-channel flighted stationary screen separators is provided in Table MSLS.2. Stationary screen separators are more effective for treating liquid dairy manure compared to liquid swine manure. In addition, solids fraction removed from dairy manure is relatively dry and can be handled as a solid (20 – 25% TS). Screen separated cake from swine manure has a slurry consistency (5 -10% TS). For this reason, stationary screen type separators are not generally used on swine farms using flushing and pit recharge manure removal systems; although they may be somewhat effective for separating solids from scraped swine manure.

Rotating Screen: Rotating screen separators are much less common than inclined screens. Advantages of rotating screens are their compact size, and they have slightly better separation efficiency for low solids swine manure than stationary screens. Cake TS concentration is also higher for swine manure than gravity screens. The available separation efficiency data for rotating screen separators is given in Table MSLS.3.

Screw Press: A summary of the available data for screw press separators is given in Table MSLS.4. Separation efficiency of screw presses is highly dependent on the TS content of the influent manure. Separation efficiency increases as influent TS concentration increases. Figure MSLS.11 shows the relationship between influent solids concentration, separation efficiency, and material through-put for screw presses treating dairy manure. Presses are best used to provide primary treatment for dairy and swine manure with a total solids content of 3% or more. The main advantage of screw press separators is the high solids concentration of filter cake for both dairy and swine manure. Often, dairy solids separated by screw press filters are recycled back to the barn as bedding.

Belt Press: A summary of available data for belt press separators is given in Table MSLS.5. Separation Efficiency is dependent on TS concentration of influent, tightness of weave of the press fabric, and to some extent pressure applied by rollers. Belt presses have better performance with swine manure than all but centrifuge separators, and produce a slightly less solid cake than screw press separators.

Brushed Screen Roller Press: Less farm-scale data is available for brushed screen roller presses compared to the other 5 separators in this report. Separation efficiency is function of screen size and influent solids content. Cake solids content is similar to that produced by screw presses. A summary of available data for brushed screen roller presses is given in Table MSLS.6.

Centrifuge: Centrifuge separators are unique among the devices reviewed in this report in that separation efficiency is not dependent on the ability of manure solids to pass through a hole. Separation efficiency is highly dependent on influent solids content, however. In general, the more dilute the influent, the faster the centrifuge must spin to achieve the same separation efficiency. Centrifuges give the best separation efficiency for swine waste, provided cylinder speed is matched to influent TS concentration. The main drawback to centrifuge separators is the high maintenance and energy costs associated with a constantly moving mechanical device.

Table MSLS.2. Summary of Separation Efficiency Data for Stationary Screen Separators Treating Dairy and Swine Manure (from Graves et al. 1971; Shutt, et al., 1975; Piccinini and Corellini, 1987; Auvermann and Sweeten, 1992; Zhang and Westerman, 1997; Fulhage and Hoehne, 1998; Møller et al., 2000; Chastain et al., 2001a; Hjorth, 2010).

Manure Type	Screen Opening (mm)	Influent TS (% wb)	Separation Efficiency (%)						Cake TS (% wb)
			TS	VS	TN	Org-N	TAN	TP	
Dairy	NA	1.5	19	24	13	NA	NA	18	19
	0.5	NA	55 – 74	57 – 75	25 - 42	33 – 52	18 – 33	NA	NA
	1.5	3.8	61	63	49	52	46	53	20
	1.5	NA	45	50	17	19	8	11	23
	3.0	7.1	56	NA	49	NA	NA	49	NA
Swine	1.0	1.0 – 4.5	6 - 31	5 - 38	3 - 6	NA	NA	2 - 12	5
	1.0	0.2 – 0.7	35	NA	NA	NA	NA	NA	9
	1.5	0.2 – 0.7	9	NA	NA	NA	NA	NA	6

Table MSLS.3. Summary of Separation Efficiency Data for Rotating Screen Separators Treating Dairy and Swine manure (from Hegg et al., 1981; Piccinini and Corellini, 1987; Zhang and Westerman, 1997).

Manure Type	Screen Opening (mm)	Influent TS (% wb)	Separation Efficiency (%)				Cake TS (%wb)
			TS	VS	TN	TP	
Dairy	0.75	0.5 – 3.0	0 - 14	NA	NA	NA	6 – 11
Swine	0.75	2.5 – 4.1	4 – 8	NA	NA	NA	16 - 17
	0.80	1.0 – 4.5	5 - 24	9 - 31	5 - 11	3 – 9	12

Table MSLS.4. Summary of Separation Efficiency Data for Screw Press Separator Treating Dairy Manure, Anaerobically Digested Dairy Manure, and Swine Manure (from Converse et al., 1999; Converse et al., 2000; Gooch et al., 2005; Møller et al., 2000; Chastain, et al., 2001b; Wu, 2007; Hjorth et al., 2010).

Manure Type	Screen Opening (mm)	Influent TS (%)	Separation Efficiency (%)						Cake TS (%wb)
			TS	VS	TN	Org.-N	TAN	TP	
Dairy	0.50	2.6	25	NA	8	13	2	6	26
	0.75	10.	70	77	24	29	20	24	25
	2.38	2.0	16	NA	NA	NA	NA	9	26
	2.38	10.	47	NA	NA	NA	NA	29	34
	2.38	5.0	33	---	13	20	3	10	29
	3.00	7.1	40		13	---	---	21	NA
Anaerobically Digested Dairy	0.50	7.4	50	56	16	18	14	24	24
	0.50	8.3	46	52	17	20	14	20	25
	2.25	5.5	4	5	1	2	1	1	29
Swine	0.50	3.0	7	10	5	7	4	8	23 – 34
	0.50	5.0	16	29	12	16	10	16	23 – 34
	0.50	7.0	24	32	20	24	17	24	23 – 24
	0.50	NA	15	20	9	16	7	15	28
	0.90	5.7	28	NA	6	NA	NA	12	NA

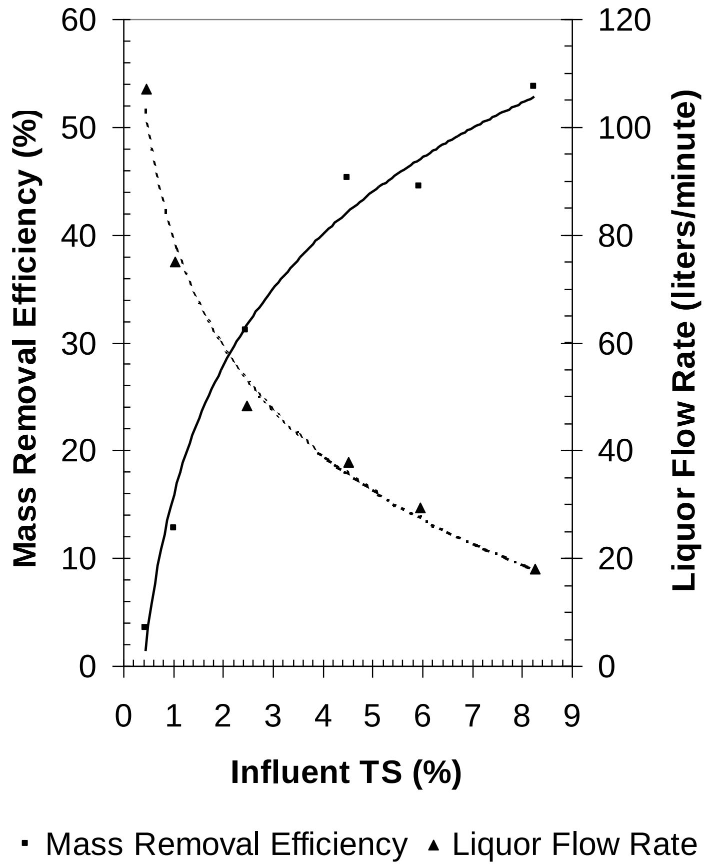

Figure MSLS.11. Effect of Influent TS Concentration on Performance of Screw Press Separators treating Dairy Manure (from Burns and Moody, 2001; Hamilton, 2006).

MSLS.6 Table MSLS.5. Summary of separation efficiency data for belt presses treating dairy and swine manure (Møller et al., 2000; Ford and Fleming, 2002; Fernandes et al., 1988; Pieters et al., 1999; Hjorth et al., 2010).

Manure Type	Belt Opening (mm)	Influent TS (%)	Separation Efficiency (%)				Solids Fraction TS (%)
			TS	VS	TN	TP	
Dairy	1.0 to 2.0	7.1	32	NA	10	15	15
	0.1	3.0	47	NA	32	18	18
Swine	0.1	8.0	59	NA	35	21	14
	1.0 to 2.0	5.7	22	NA	10	20	19

MSLS.6. **Summary of Separation Efficiency Data for Brush Screen Roller Presses Treating Dairy and Swine Manure (Pos et al., 1984; Rorick et al., 1980; Gooch et al., 2005).**

Manure Type	1st and 2nd Screen Opening (mm)	Influent TS (%)	Separation Efficiency (%)				Solids Fraction TS (%)
			TS	VS	TN	TP	
Dairy	3.2/3.2	5.2	36	41	15	15	14
	NA	4.5	10	NA	NA	NA	26
	NA	9.9	25	NA	NA	NA	30
	NA	10.3	40	45	18	13	24
Swine	1.6/1.6	6.3	21	25	6	6	20

Table MSL.7 . Summary of Data from Centrifuge Separators Treating Dairy and Swine Wastes (Reinman, 1989; Møller et al., 2002; Westerman and Ogejo, 2005; Møller et al., 2007; Hjorth et al., 2010).

Manure Type	Cylinder Speed (rpm)	Influent TS (%)	Separation Efficiency (%)		
			TS	TN	TP
Dairy	4,100	4.5	55	27	79
	NA	6.0	44	23	48
	4,100	6.4	65	49	82
	2,200	7.0	63	29	55
Swine	5,000	1.5	51	21	61
	4,100	2.6	33	13	66
	4,100	5.3	60	29	62
	2,200	4.0	52	17	70
	2,200	5.1	51	17	71
	2,200	6.8	70	36	82
	NA	7.0	70	32	52
	2,050	8.9	69	34	87

Defined Separation Efficiencies Based on Process Factors

Separation efficiencies to use in the Chesapeake Bay Model provided pertinent process factors are known for stationary screens, screw press, belt press and centrifuge separators are given in Tables MSLS.8 through MSLS.10.

Table MSLS.8. Defined Separation Efficiencies for Stationary Screen Separators based on Process Factors.

Type of Manure	Screen Opening Size (mm)	Influent TS Content (%)	~~Removal~~ Separation Efficiency (%)	
			NSE	PSE
Dairy	1.5 or less	2-7	15	29
Swine	1.0 or less	1-10	4	7

Table MSLS.9. Defined Separation Efficiencies for Screw Press Separators based on Process Factors.

Type of Manure	Screen Opening Size (mm)	Influent TS Content (%)	~~Removal~~ Separation Efficiency (%)	
			NSE	PSE
Dairy	2.5 or less	<3	8	6
		3-10	13	10
		>10	24	24
Swine	0.1	3-5	5	8

Table MSLS.10. Defined Separation Efficiencies for Belt Press Separators based on Process Factors

Type of Manure	Belt Opening Size (mm)	Influent TS Content (%)	~~Removal~~ Separation Efficiency (%)	
			NSE	PSE
Dairy	1.0 to 2.0	0-5	10	15
Swine		0-7	10	20
Swine	0.1	0-10	30	20

Rotating screen and brushed screen roller separators require a great deal of adjustment to consistently separate manure solids. The default values of NSE and PSE given in Table MSLS1 for these devices should be used in the Chesapeake Bay Model unless direct monitoring data is available.

If the TS content of influent dairy or swine slurry, and the cylinder speed of a decanting centrifuge are known, the values for separation efficiencies given in Table MSLS.11 may be used for the Chesapeake Bay Model.

Table MSLS.11. Defined Separation Efficiencies for Centrifuge Separators Treating Dairy and Swine Manure based on Process Factors.

Manure Type	Influent TS (%)	Cylinder Speed (rpm)	~~Removal~~ Separation Efficiency (%)	
			NSE	PSE
Dairy	< 4.0	4,100	25	50
	4.0 to 6.0	4,100	25	50
	>6.0	2,200	25	50
Swine	< 2.0	5,000	10	50
	2.0 to 4.0	4,100	10	65
	4.0 to 7.0	2,200	15	70
	>6.0	2,050	20	70

Ancillary Benefits of Mechanical Solid-Liquid Separation

Mechanical solid-liquid separation does not remove nutrients from the manure stream. The stream is essentially divided into two streams one with solids higher than the original manure and one with solids content lower than the original manure. Solid-liquid separation is often used as the primary treatment step prior to biological treatment such as a treatment lagoon. In such cases, solid-liquid separation reduces the organic loading on anaerobic or aerobic treatment processes, and may also reduce the rate of sludge build-up. In recent years, it has become more common to use solid-liquid separation to dewater anaerobically digested slurry on dairy farms (*e.g.* Gooch et al., 2005). In such cases, solid-liquid separation is used as the final treatment step prior to storage, land application, or composting of separated solids. Other reasons for solid-liquid separation in manure handling are to produce stackable solids that can be re-used as bedding on dairy farms, to facilitate off-farm transport of manure for composting or to remote fields, to remove solids to facilitate irrigating manure.

Potential Hazards of Solid-Liquid Separation

There are very few environmental hazards with solid-liquid separation. The only potential hazard is that farmers may underestimate volumes of cake and effluent produced by the separator, which could result in overflow of concentrated pollutants into waterbodies.

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9. Wet Chemical Treatment

Wet chemical treatment of manure involves three processes: **Precipitation**, **Coagulation**, and **Flocculation.** Suspended solids are created from dissolved nitrogen and phosphorus by precipitation. Coagulation and flocculation enhance the ~~removal~~ separation of suspended solids by bunching individual particles into larger, more settleable groups of solids. All three processes require settling or mechanical solid-liquid separation to remove nutrients from the manure.

Wet Chemical Treatment Terminology

Precipitation is the formation of solid particles -- generally colloidal in size -- from dissolved solids by adding chemicals to transform soluble ions into less soluble precipitates.

Coagulation is the removal of repulsive forces between small particles – usually by reducing electrical charges – to form larger, more easily removed particles.

Flocculation is the binding together of small particles to form larger, more cohesive particles called flocs.

A **Precipitate** is an insoluble chemical compound created through a chemical reaction between dissolved ions.

A **Precipitant** is a chemical used to activate precipitation reactions in solution.

A **Colloidal Particle** is a very fine particle (smaller than 0.1 micron) that remains suspended in water under quiescent conditions.

Suspended Solids are the non dissolved particles that remain after water is evaporated from a liquid sample. By definition, suspended solids are solid particles that are retained on a 1.5 micron filter (APHA, 2012).

Dissolved Solids are particles that remain after water is evaporated from a sample, but are dissolved (exist as separated ions) in water. By definition (APHA, 2012), they are solids that pass through a 1.5 micron filter.

Settleable Solids are non-dissolved particles that settle out of a liquid under quiescent conditions.

Chemical Treatment not Covered in this Report

Chemicals added to Treat Poultry Litter generally lower litter pH, which reduces the loss of ammonia gas to the atmosphere by shifting the auto dissociation of ammonia towards the non-volatile ammonium ion. Some additives also causes precipitation of orthophosphate phosphorus into less water soluble forms of phosphorus. Although chemical additions to poultry litter may be an effective method of temporary immobilizing nitrogen and phosphorus, its action takes place within animal housing, and may more accurately be described as manure storage rather than treatment.

Two additional physical processes, adsorption and absorption, often associated with chemical treatments are not covered in this report. **Adsorption** is immobilization of nutrients by fixing them to the surface of chemical compounds or materials. An example of adsorption is fixing ammonia nitrogen on the surface of certain clays, soaps, and zeolites (Johnston et al., 1981; Bernal and Lopez Real, 1993). **Absorption** is the incorporation of nutrients within the structure of a chemical or material. Bedding absorbs moisture from manure. The absorbed liquid may contain dissolved nitrogen and phosphorus. However, using bedding does not reduce the mass of nutrients leaving the barn.

Types of Manure Used

Precipitation is used as the first step in removing nutrients from liquid and slurry dairy and swine manure. Precipitation is also a polishing step in removing phosphorus from clarified liquids, lagoon effluent, composting leachate, aerobic treatment effluent, and anaerobic digester effluent originating from all types of manure. Flocculation and coagulation are used to enhance ~~removal~~ separation of nutrients by settling and mechanical solid-liquid separation from all types of manure liquid and slurry.

Transfer Efficiencies Wet Chemical Treatment

There are two primary types of wet chemical treatment: 1) chemcial additions to enhance separation of settling devices and mechanical solid-liquid separators, and precipitation 2) Formation of precipitants from clarified manure liquids. Black box approximations of settling and mechanical solid-liquid separation are given in Figures STTL.1 and MSLS.1. Figure WCT.1 is a black box schematic of chemical precipitation of clarified liquid manure.

Since neither settling devices, mechanical solid-liquid separators, nor chemical precipitators remove nitrogen through volatilization, NVE wet chemical treatment is always zero. Nitrogen and phosphorus separation efficiencies as calculated as shown in Equations WCT.1 and WCT.2:

$$\textbf{NSE} = \frac{\textbf{(Mass of TN in Sludge, Cake, or Precipitated Solids)}}{\textbf{(Mass TN in Influent)}} \textbf{ X100} \qquad \text{WCT.1}$$

$$\textbf{PSE} = \frac{\textbf{(Mass of TP in Sludge, Cake or Precipitated Solids)}}{\textbf{(Mass TP in Influent)}} \textbf{ X100} \qquad \text{WCT.2}$$

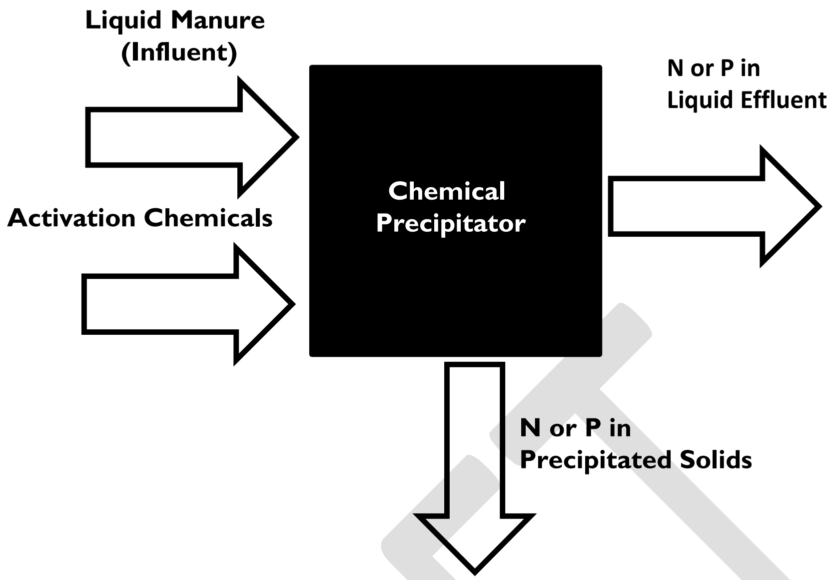

Figure CP1. Black Box Schematic of a Chemical Precipitator.

Default Transfer Efficiencies of Wet Chemical Treatment

Since ~~removal~~ separation of phosphorus and nitrogen by wet chemical treatment is heavily dependent on chemical dosing, and the ultimate ~~removal~~ separation of precipitated, coagulated, and flocculated solids relies on a secondary ~~removal~~ separation system (settling, mechanical solid-liquid separation), no transfer of nutrients can be assumed in Chesapeake Bay Model unless monitoring data from an individual treatment system is provided.

Review of Available Science on Wet Chemical Treatments

The first step of wet chemical treatment is precipitation. In precipitation, dissolved ions are chemically transformed to non-soluble, colloidal crystals called precipitates. Solids are further removed from suspension through the use of coagulating and flocculating agents. Coagulants collapse the electrical, generally positive, charges that repel particles. With the repulsive charges removed, colloidal and suspended particles stick together to form conglomerates. The conglomerated particles are weak and gelatinous in consistency. Flocculants are filamentous chemicals that bind together and strengthen conglomerated particles allowing them to settle at much greater rate. Strengthening particles with flocculants also allows the particles to remain intact when subjected to mechanical methods of solid-liquid separation.

Location of Chemical Addition in the Manure Handling System

Figure WCT.2 shows a generic layout of manure treatment on a dairy farm. Not all of these technologies are currently being used on dairy farms -- the figure is presented to show possible locations within the manure treatment system where chemicals could be applied for nutrient removal. In location A (just before a solid-liquid separation) coagulants and flocculants are used to enhance solids separation and thus separate P and N form the liquid stream. In location B (effluent of anaerobic digester) coagulants and flocculants are added to enhance solids ~~removal~~ separation and precipitants along with coagulants and flocculants to remove dissolved P and N. Activation chemicals can also be added along with coagulants and flocculants added in Location C (after nitrification) and D (after advanced treatment systems such as enhanced biological removal reactors or denitrification reactors) to remove dissolved P. Due to higher solids content, applying chemical at location A may require a higher chemical dosage compared to other locations, and may also lead to nutrient deficient conditions if manure treatment technologies downstream of the separator are biological systems. If the manure treatment system is not set up for continuous chemical P removal, P can be removed by adding chemicals to storage tanks before land application. When using the batch method, producers should be sure to have contingency plans to flush liquid from barns if recycled, treated manure is used to clean barns.

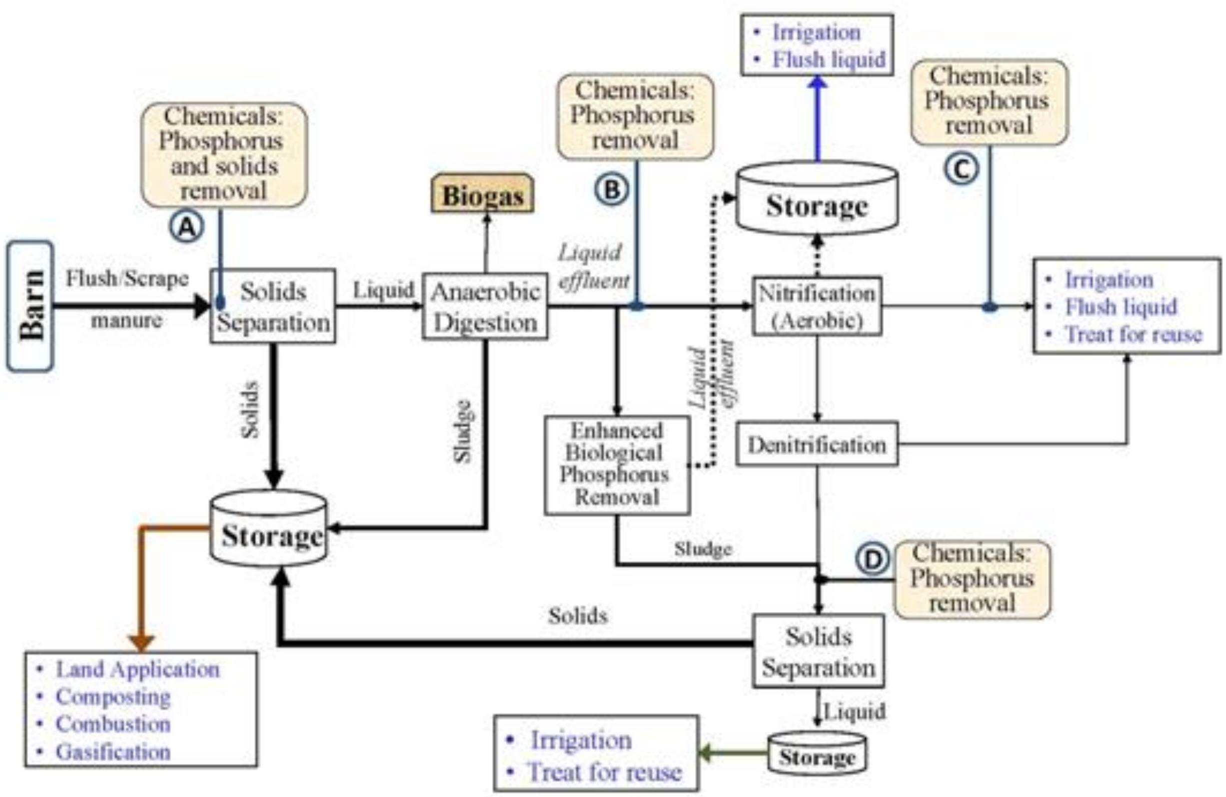

Figure WCT.2 . Generic Dairy Manure Handling System Showing Areas to Add Chemicals for Treatment.

Precipitation and Coagulation Using Metal and Calcium Salts

The nature of precipitates formed during chemical P ~~removal~~ separation is not well understood. Some properties of the chemicals for P ~~removal~~ separation and a partial list of the solids that can be formed by adding metal and calcium salts are presented in Table WCT.1. Other solids not containing phosphates that can be formed are also included in Table WCT.1.

Table WCT.1. Properties of Metal and Calcium Salts used to Remove Phophorus by Precipitation and Some Precipitates Formed.

Precipitant	Molecular Weight (g/mole)	Availability		Possible Precipitates
		Form	Concentration (%)	
Aluminum sulfate (Alum) $Al_2(SO_4)_3 \cdot 14H_2O$	594	Liquid	4.3 to 4.5 Al	Aluminum phosphate Aluminum hydroxide
		Dry	9.0 to 9.2 Al	
Aluminum chloride $AlCl_3$	133.5	Liquid	5.3 to 5.8 Al	
Ferric chloride $FeCl_3$	162.2	Liquid	11.3 to 14.5 Fe	Ferric phosphate Ferric hydroxide
Ferric sulfate $Fe_2(SO_4)_3 \cdot 9H_2O$	562	Granular	18.5 to 20.5 Fe	
		Liquid	10 to 14 Fe	
Calcium hydroxide (Lime) $Ca(OH)_2 \cdot 2H_20$	74.1	Dry	63-73 (CaO)	Hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ Dicalcium phosphate Tricalcium phosphate Calcium carbonate
		Slurry	15-20 (CaO)	
		Powder	85-99 (CaO)	

Aluminum and Iron Salts behave similarly when used for phosphorus removal. The simple chemical reactions for precipitating phosphorus using aluminum and iron salts are given in Equations WCT.3 and WCT.4. Under ideal circumstances, 55 pounds of iron or 28 pounds of aluminum will precipitate 100 pounds of phosphate. However, there are many competing reactions that occur associated with these metals including the effects of alkalinity, pH, trace elements, and organic complexes when these chemicals are added to manure. Because of these competing reactions, the required chemical doses are usually larger than those predicted by the chemical relationships of WCT2 and WCT3. The exact quantities are usually established using bench scale tests. The optimum pH range for P removal using Al and Fe is 4 to 7.

$$Al^{3+} + PO_4^{3-} \rightarrow AlPO_4 \quad \text{WCT.3}$$

$$Fe^{3+} + PO_4^{3-} \rightarrow FePO_4 \quad \text{WCT.4}$$

When **Lime** (Figure WCT3) is added to liquid manure, it first reacts with the natural alkalinity. The reaction with alkalinity produces calcium carbonate, $CaCO_3$ (WCT.4). As more lime is added and alkalinity consumed, the pH of the manure increases. When manure pH increases beyond a value of 10, the excess calcium ions in solution react with phosphate to precipitate hydroxyapatite (WCT.5). Thus, the quantity of lime required to precipitate phosphate depends primarily on the alkalinity of manure. The optimum pH for P removal using lime is high (over 10), thus if lime is used to remove P, the pH of the resulting liquid manure may need to be adjusted if a lower pH is desired at the final point of use.

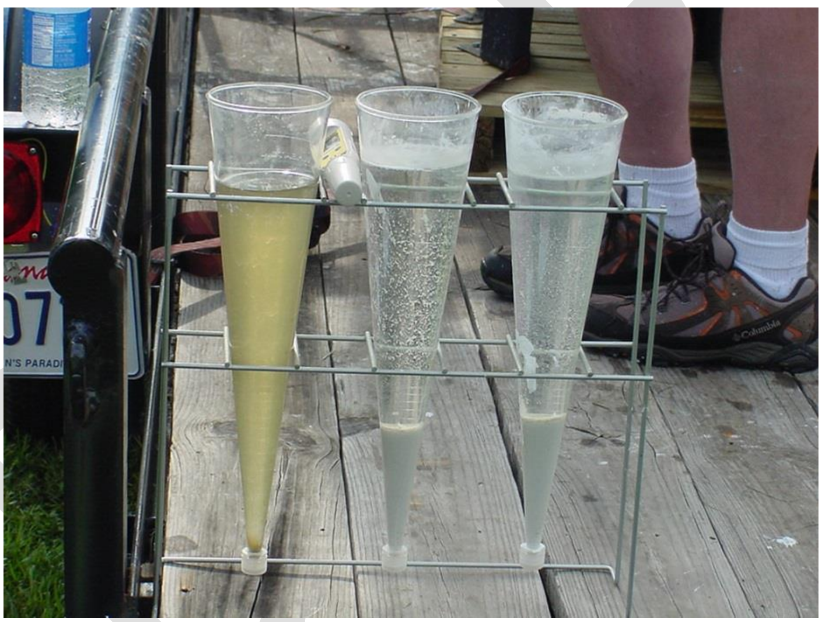

Figure WCT.3. Wastewater from an Alligator Ranch before and after Lime Treatment (YouTube: OSUWasteManagement).

$$Ca(OH)_2 + HCO_3^- \rightarrow CaCO_{3(S)} + H_2O \qquad \text{WCT.5}$$

$$10Ca^{2+} + 6PO_4^{3-} + 2OH^- \leftrightarrow Ca_{10}(PO_4)_6(OH)_2 \qquad \text{WCT.6}$$

Figure WCT.4 shows the effect of adding metal and calcium salts to enhance removal of dissolved P from dairy manure by settling. The 40% Ferric chloride solution was not added in doses exceeding 2,000 mg/l, because Fe salts produce gases that make solids float. For this reason, FeCL2 is more commonly used as an additive in Dissolved Air Flotation Systems (DAF), which is not covered in this report.

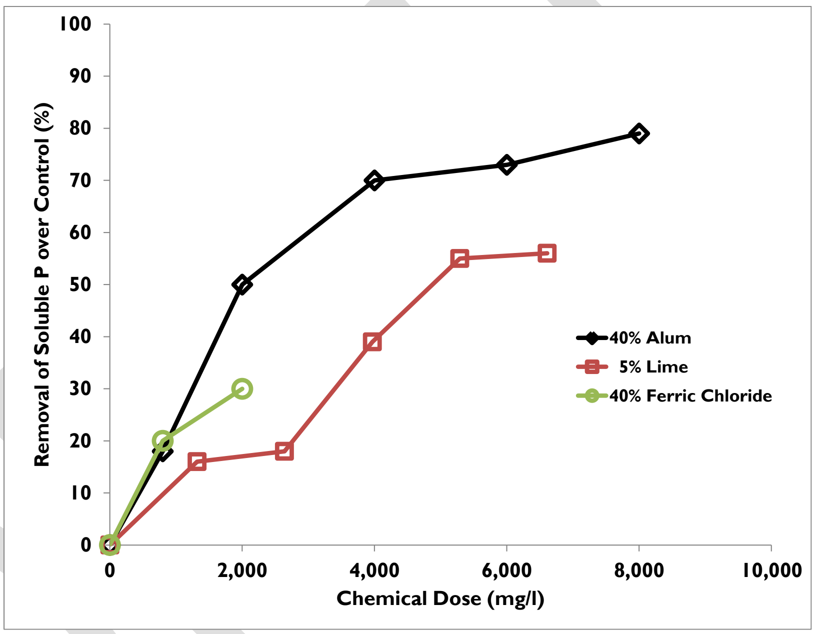

Figure WCT.4. Removal of Soluble Phosphorus from Separated, Sand-Bedded Dairy Manure after Adding Alum, Lime, or Ferric chloride and Settling for One Hour (from Kirk et al., 2003).

The metal salts of iron, aluminum, and calcium are also the most common **coagulants** used in agriculture. When these salts are added in sufficient quantities to manure, the newly formed particulates present in the manure coagulate to form larger particles. Some of the parameters that highly influence the effectiveness of chemical coagulation include pH, suspended solids, dissolved organic matter, type and dose of chemical used, and where the chemical is applied in the manure treatment and handling system.

Figure WCT.5 shows the effect of alum, lime and ferric chloride in separating total P from dairy manure by settling. The results of Figure WCT.5, which used the same manure as the study shown in WCT.4, show that alum and lime are equally effective at separating TP from the manure stream. The liquid manure used in this study contained 196 mg/l soluble P and 2,831 mg/L Total P (< 10% Soluble). These figures taken together suggest that, although alum may act as a better precipitant than lime, the two chemicals have similar coagulant properties.

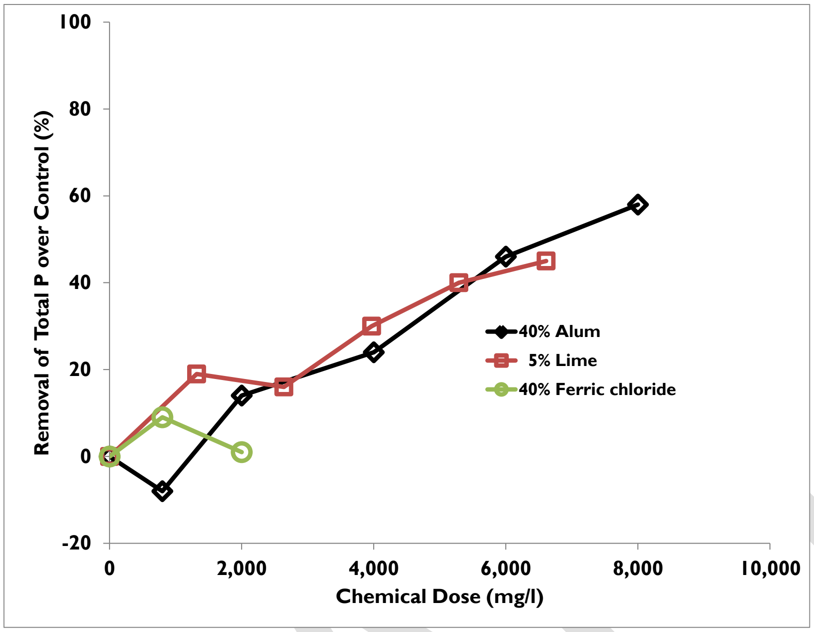

Figure WCT.5. Removal of Total Phosphorus from Separated, Sand-Bedded Dairy Manure after Adding Alum, Lime, and Ferric chloride and Settling for One Hour (from Kirk et al., 2003).

Figures WCT.4 and WCT.5 suggest that the removal of phosphorus from manure is dependent on the dosing rate of chemicals. In other words, the more activation chemical added, the more phosphorus is removed. Dosing rate is calculated as the ratio of the activate element in the precipitant (Al, Ca, Fe) to the element to be removed (P). Figure WCT.6 shows the effect of alum dosage on the removal of Total P from dairy manure by settling.

Determining the dosing rate can be very difficult, and due to the complex chemistry of manure, is virtually impossible to achieve without experimental data. A laboratory technique called a **Jar Test** is used to determine the optimum dose of chemicals needed for a particular wastewater. The jar test requires a container (1 liter volume), a timer, a mixer (one with variable speed preferred), and graduated cylinders (or a way of measuring volume). In a jar test, a sample of manure to be treated is poured into a series of beakers. Different doses of the chemicals are then applied to each beaker. The contents are rapidly stirred immediately after the chemical is applied to simulate rapid mixing followed by gentle stirring to allow flocculation to occur. After some time, the stirring is stopped to allow the flocs formed to settle. The most important things to note during the jar test are the floc size and clarity of the supernatant liquid.

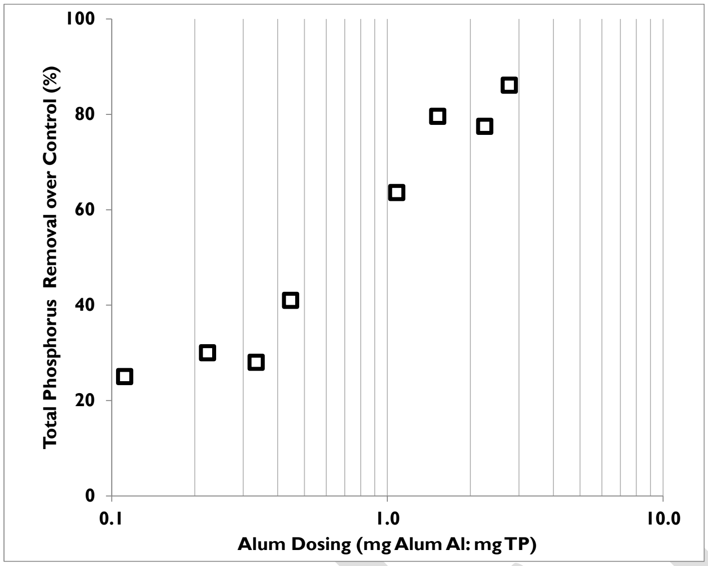

Figure WCT.6. Effect of Alum Dosing on Total Phosphorus Removal Efficiency after Settling for 24 Hours. (Sherman, et al., 2000; Kirk et al., 2003)

The following procedure is suggested for performing the jar test for metal and calcium salts. Measure 1L of manure sample into the 1L container (or containers if more than 1). Select the chemicals and the range or concentrations to be tested. Obtain the chemicals and prepare desired concentrations to be used in the test. Turn the mixer on and set the speed to high (100 rpm, if mixer has a speed indicator). Add the selected volume or dose of chemical to the each jar. Mix for about 2 min at the high speed and then reduce the speed to about 30 rpm and mix for about 5 min. After mixing, settle the chemically treated manure for 60 min. Observe the container noting particle size, settling characteristics, and the clarity of the supernatant. Analyze the supernatant for P, suspended solids, and color to determine which dose produced the desired level of treatment. Use the results to select the chemical or combination of chemicals that achieves the desired result to calculate the quantity of the selected chemical required.

Coagulation and Flocculation using Organic Polymers

Polymers are high molecular weight compounds usually made of synthetic material. Polymers can be cationic (positively charged) or anionic (negatively charged). The fibrous nature of polymers allows them to form bridges between particles, and their electrical charges allow them to attract particles and act as coagulants. The most common flocculants used for manure are cationic polyacrylamides (PAM). Polymers may be supplied as a prepared stock solution ready for addition to the treatment process or as a dry powder. The best approach in selection of polymers is to contact a supplier or manufacturer for recommended practice and use.

Flocculants in combination with coagulants or flocculants alone are used to enhance separation in screen type mechanical solid-liquid separators (stationary screens, rotating screens, screw press, belt press, brushed screen roller press). The fibrous flocculant adds strength to conglomerated particles. Without the added strength of the flocculant these particles are likely to be squeezed through or smeared across the screens. Effect of dosing of cationic PAM to enhance removal of swine manure phosphorus through screening is shown in Figure WCT.7.

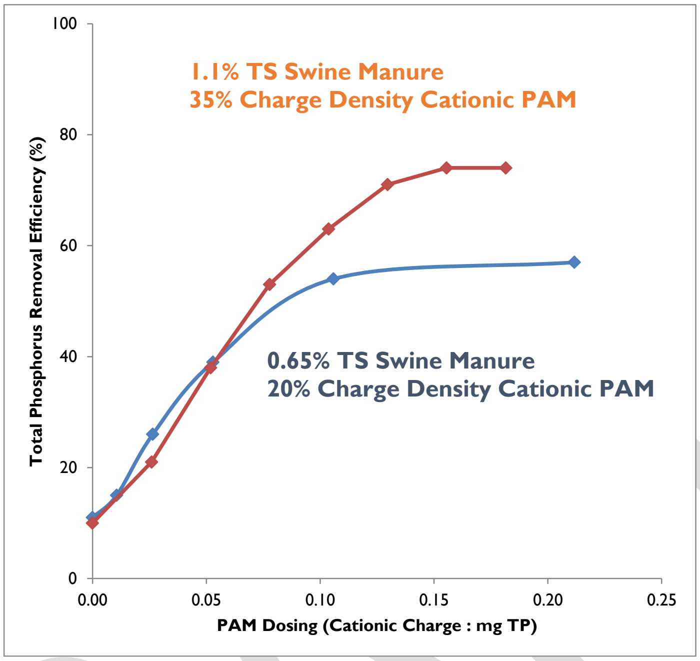

Figure WCT.7 Effect of Cationic Polyacrylamide Flocculant Dosing on Total Phosphorus Remvoval from Swine Manure by Screening (from Vanotti and Hunt, 1999; Vanotti et al., 2002).

If polymer is to be used alone or with coagulants to remove P, **the jar testing procedure** outlined for metal and calcium salts should be done in the following three steps: add chemical to manure and mix for 2 min. at 100 rpm; then add polymer and mix for 2 min. at 200 rpm and then reduce the speed to 30 rpm and mix for a further 5 min.; and then settle for 60 min. After settling, analyze the supernatant as suggested above.

Precipitation of Struvite (Magnesium Ammonium Phosphate)

Precipitation of Struvite ($MgNH_4PO_4{\bullet}H_2O$) has been the curse of swine farmers as long as anaerobic lagoon effluent has been used to flush hog barns. Struvite deposits whenever excess Mg^{+2}, NH_4^{+1} and $PO4^{-3}$ are available, reducing conditions exist, and seed crystals bump into each in turbulent flow. In other words crystalline struvite deposits in pipes, pipe fittings, and on pump impellors. Equally calamitous conditions exist when pumping anaerobic digester (Borgerding, 1972) and swine lagoon effluent (Booram et al, 1975). Buchanan et al. (1994), Ohlinger et al (1999), and Nelson et al. (2000) led early efforts to turn the curse into a blessing by exploring the conditions under which struvite is formed with the intention of precipitating the salt before it enters pipe networks. The common ingredients were adjusting pH to create basic conditions, and adding sufficient Mg^{+1} to stimulate precipitation. Under laboratory conditions, removal efficiency of TP by struvite precipitation runs between 80 and 90% (Burns et al., 2003; Nelson et al., 2003; Laridi et al., 2005). The kinetic experiments led to development of a cone-shaped fluidized bed crystallizer (Figure WCT.5) to effectively remove struvite from lagoon effluent (Bowers and Westerman, 2005a). Total Phosphorus removal efficiency of the cone crystallizer using synthetic swine manure and controlled conditions was 60 to 80% (Bowers and Westerman, 2005b); however using effluent from a covered lagoon digester on a working swine farm gave mean TP removal efficiency of 55% ± 10% and orthophosphate phosphorus removal efficiency of 65% ± 5% (Westerman et al., 2010).

Figure WCT5. ~~Demontration~~Demonstration of the Latest Generation of Cone Struvite Crystallizer on a Dairy Farm near Massey, Maryland (Sassafrassriver.org).

Removal of TP from dairy manure by struvite is much more difficult. Sheffield et al. (2005) found that the cone crystallizer removed TP from untreated dairy manure in the 8 to 19% range. Shen et al. (2011) found that suspended solids and excess Ca^{+2} inhibited struvite precipitation in liquid dairy manure. They were able to increase TP removal efficiency of dairy manure above 60% by reducing manure to pH 4.5, adding EDTA or oxalic acid to remove Ca^{+2}, and raising pH to 7.5.

Forty-five pounds of ammonia nitrogen removed for every 100 pounds of phosphorus precipitated as struvite. Removal efficiency of TN depends on the TAN:TP ratio of the treated manure and pH at time of precipitation.

Defined Separation Efficiencies based on Process Factors

Transfer efficiency of N and P by wet chemical treatments is highly dependent on chemical dosing. For this reason, defined separation efficiencies for settling and mechanical solid-liquid separation given in previous chapters should be used with the CBWM instead of estimating the effect of enhancing these processes using activation chemicals. Monitoring data from individual units should be used for separation efficiencies of lime and struvite precipitation.

Ancillary Benefits of Wet Chemical Treatment

Chemical precipitation is a well-established technology and is widely practiced in the water and wastewater treatment processes. Equipment and chemicals are readily available to adapt these practices to agriculture. Precipitation can yield very high phosphorus removal efficiency at optimum pH and chemical dosing. An ancillary benefit is production of high phosphorus content fertilizer from relatively dilute manure. This chemical fertilizer may be sold at a premium resulting in an extra source of revenue for the farmer. The lower cost of transporting the highly concentrated fertilizer increases the chance that the nutrients will be shipped out of the Chesapeake Bay Watershed. The chemicals produced, whether struvite, hydroxyapatite, or Aluminum phosphate, have a known composition and can be applied precisely to meet the needs of a receiving crop – inside or outside the watershed.

Using coagulants and flocculants on raw manure will increase the separation efficiency of downstream processes. The resultant sludge can be dried and transported further at lower cost, increasing the chance that the manure nutrients will be shipped out of the Chesapeake Bay Watershed.

Disadvantages of Wet Chemical Treatments

The principal disadvantage of wet chemical treatment is cost of activation chemicals. Because of this cost, producers may attempt to reduce dosing and therefore render the treatment ineffective. Also attempts to recover more nutrients by adding additional chemicals can be counterproductive because overdosing can reduce the treatment effectiveness. Other costs of implementation are skilled labor required to handle chemicals and determine proper dosing, proper storage and handling of potentially corrosive chemicals, disposal of chemical containers, and the specialized pumping and plumbing required to deliver the chemicals.

Compared to biological P removal, wet chemical treatments produce excessive sludge. For example lime addition can increase manure solids by up to 50%. Competing reactions and varying levels of alkalinity and other factors make calculation of dosing difficult; therefore, frequent jar tests are necessary for confirmation of optimal treatment.

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10. Data Collection and Reporting Protocols for Reporting Data Driven (Level 3) Transfer Efficiencies

This section describes the general expectations and protocols that are proposed as a data-driven BMP category that can apply to a manure treatment system that has monitoring data to determine the nitrogen load that will be eliminated from the primary manure stream. This section does not apply to the Default (Level 1) and Defined (Level 2) categories described elsewhere in this report. **Data Driven (Level 3) Transfer Efficiency** can be applied to a treatment system that utilizes one or more manure treatment technologies described previously in this report. The technologies being used may be proprietary or non-proprietary and may be used in any sequence to produce one or more end products for subsequent transport or land application. On-farm or multi-farm, centralized manure~~T~~ treatment systems reported under this category will have unique transfer efficiencies that must be determined using monitoring data collected on site. The reported performance data will include the mass of N volatilized as gaseous emissions. If mass of N lost through emissions is not monitored, then a quantifiable mass balance of the system's N inputs and outputs is required. The calculated transfer efficiency will vary annually from system to system. Transportation or land applications of any end products from these types of systems should be reported via NEIEN under separate BMPs (e.g. Manure Transport, manure injection/incorporation). Manure treatment systems that lack adequate annual performance data to support a Data Driven Transfer Efficiency (i.e., Level 3) should be reported using the appropriate Level 1 or Level 2 Transfer Efficiency for that system's primary manure treatment technology.

Existing monitoring data collection and reporting requirements will vary by manure treatment system and jurisdiction and/or supplemental funding program(s), if any. Permit requirements may exist for some treatment systems, but will also vary based on a variety of factors, including whether the treatment system is associated with a permitted CAFO or AFO, the capacity and type of system, the system's air emissions, and applicable state and federal regulations that cover relevant areas such as air emissions or the handling/treatment/disposal of animal manure.

This chapter provides some basic guidance for the partnership with the understanding that any specific regulatory and programmatic requirements for the monitoring, sampling or reporting of data for a manure treatment system is determined by the jurisdiction. Given the panel's scope, and due to the potentially complex nature of federal and state regulations, program requirements and guidance, the panel understood early on that it would only be able provide general reporting and monitoring guidance ~~to be used~~for the partnership when seeking to establish a category for Level 3 transfer efficiencies~~y~~ in the modeling tools. By not prescribing specific methods the panel does not inhibit the ability of state and federal partners to work with each other, producers and third parties to determine effective monitoring and verification protocols that can simultaneously ensure rigorous data collection and reporting while not being overly burdensome or costly to implement.

The panel acknowledges that some states have existing programmatic and regulatory structures that will guide ~~and inform~~ the necessary data ~~collection~~ tracking ~~and reporting~~ to ~~establish~~ report Level 3 transfer efficiencies for eligible manure treatment systems. Other states may not have such programmatic structures at this time because these treatment technologies may only be in pilot stages or are not common enough in their state to warrant more explicit regulations or guidance. For the CBP partnership's reference, the panel coordinator solicited preliminary information from the jurisdictions in order to summarize information for states that have some existing programs or funding-mechanisms that would be the basis for their data collection, reporting and verification protocols for potentially reporting Level 3 transfer efficiencies. Maryland, Pennsylvania and Virginia fall under this category and are summarized in Table DD.1. The other jurisdictions did not provide additional information at this time, which, in no way, affects their ability to report treatment practices with Level 3 transfer efficiencies in the future.

Table DD.1 Overview of jurisdictions current monitoring and reporting requirements for animal manure treatment systems

	Basic description of current applicable program	**Types of data collected under the current program, and frequency it is reported**	**Comments**
Maryland	*Treatment systems under CAFO permit*: Very limited implementation at this time. One digester may require monitoring for compliance with CAFO permit.	The CAFO would monitor structural integrity and capacity on a daily basis. Records kept on-farm are subject to inspection.	Digestion without additional treatment steps is best reported as Level 1 or Level 2 for simplicity. More information would need to be documented in Maryland's QAPP describing the data collection and reporting requirements before these CAFO treatment systems could be reported as Level 3.
	Innovative technology funds: Two or more projects received funding as demonstrations through innovation funds (AD and combustion), which requires 1 year monitoring and quarterly reporting once operational.	MD is developing project specific monitoring related to performance, including feedstock and output nutrient values, real time energy production, and emissions. Possible that emission information will be required as part of an air quality permit.	Maryland should continue to develop such performance based monitoring and reporting for these treatment systems that receive innovation funds. If the systems continue to collect and report this information to state agencies annually these could be reported under Level 3.
Pennsylvania	*Water quality trading program*: Detailed monitoring and verification requirements written on a case by case basis.	Sampling data elements and reporting frequency are specified in each facility's plan.	Systems reported through this program could be eligible for Level 3 if EPA and PA agree that the collected and reported data is consistent with the CBP Partnership's expectations for BMP verification. Relevant details from the facility's M&V plan should be documented in the state's QAPP.
	Growing Greener and 319 funds: Could possibly fund treatment systems, though few are funded through these programs due to systems' cost. All projects must submit a final report describing the practice installed, but unlikely	Project report would include type of practice, size, location, type and number of animals, amount of manure it will treat. Report only submitted once, when funded project is installed.	PA noted this is a doubtful source of implementation data since it is submitted once, not annually.

	this program will be a source of reporting data for BMP implementation.		
	PennVest: Available to fund treatment projects. Generally does not require monitoring beyond completion of installation. Many projects also receive USDA funding which does not report monitoring data.	Unclear what types of data are collected or provided in report, which appears to be limited to project completion.	With this amount of information the system is better suited for reporting under Level 1 or Level 2, if reported at all. However, systems funded in this manner may report their data under other programs, e.g. water quality trading.
Virginia	Individual permits and the VPA AFO General Permit. Four options for permitting AFOs in Virginia: two are general permits and two are individual permits.	Owner of the AFO facility required to sample, analyze and keep record of TKN, Ammonia N, TP, total K, Ca, Mg, and moisture content. Composite sample must be analyzed for each of the parameters once each year, or every 3 years for poultry. A sample is taken from each type of waste stream produced by treatment system used by the AFO. Data elements collected as required under the permits would be inspected by DEQ staff at the facility. GP requires recordkeeping but not reporting, while individual permits VPDES CAFO IP and VPA AFO IP) require annual reporting to regional DEQ offices electronically or by hard copy. Records are inspected by the regional DEQ staff.	The collected information appears sufficient for reporting these systems under Level 3, but if systems under the GPs are not reported to DEQ then they could not be reported to EPA as Level 3 BMPs and would need to be reported as Level 1 or Level 2 instead. Systems that report annually under the individual permits should already be providing the necessary information to DEQ to be reported under Level 3.
General or watershed-wide comments	The data collection, sampling and reporting requirements for state programs are highly variable due to a number of factors, e.g. regulatory vs. voluntary, cost-share vs. loan vs. grant vs. seed money for innovative approaches, etc.	Level 1 BMPs are expected to be the most commonly reported due to the relatively minimal data needs. Jurisdictions should be encouraged to strive for Level 2 and Level 3 BMPs whenever they are able to develop or enhance their ability to receive and submit the necessary data from the treatment system operator.	Monitoring, sampling and reporting requirements for any manure treatment system reported under Level 3 must be clearly documented in the jurisdiction's QAPP. If a system reports data under multiple programs, the jurisdiction only needs to document and describe the program(s) from which the data submitted to the CBP is received.

Table DD.1 summarizes applicable data collection or reporting requirements as described by Maryland, Pennsylvania and Virginia when contacted by the Panel Coordinator in the course of developing this report. The table is not intended to be a comprehensive description of applicable programs in the three states, as other programs may apply or be created in the future. The table is provided to serve as a basic reference and starting point for future discussions by the partnership as these systems start to be reported for annual progress runs. The information may be less useful to the jurisdictions who already have a deeper understanding of these programs and associated data, but others may benefit from the basic overview provided in the table. Other jurisdictions not shown in Table DD.1 may also have their own programs or may create ones in the future. The table is provided as an informational guide to illustrate how, or if, a Level 3 transfer efficiency could be reported for a manure treatment system covered under the programs shown in Table DD.1.

Systems could be covered under one or more programs based on its source funding or regulatory requirements, so each system ~~will~~may need to be described in the jurisdiction's QAPP in order for the jurisdiction and EPA to determine its eligibility, on a case-by-case basis, for a Level 3 mass transfer efficiency. For these reasons it is likely that initially only a handful of systems will report Level 3 transfer efficiencies, but that number will likely grow if implementation incentives are accelerated. If the cumulative reductions for manure treatment systems reporting Level 3 treatment efficiencies becomes > 1% of a state's net nutrient reductions for one or more progress runs, the partnership should evaluate the reporting requirements for these systems and discuss whether improvements to the data collection, reporting and verification system are warranted.

Any jurisdiction reporting a manure treatment system with a Level 3 transfer efficiency must document its data collection and reporting requirements for the associated system in its Quality Assurance Project Plan (QAPP) submitted to and reviewed by EPA. If there are variations in requirements or data collection between individual systems, the jurisdiction will need to clarify those differences in its QAPP.

Specific data collection and reporting requirements will be determined by the applicable state agency, in coordination with any appropriate federal agencies who have oversight or implementation roles (e.g., EPA or USDA-NRCS). State-federal coordination may be required in certain cases and may already occur in most instances, but, if not, it should be strongly encouraged for purposes of effective management. **In all cases, the collected and reported data will need to meet the expectations described in the CBP partnership's BMP Verification Framework.** Such a determination will be made by EPA and state partners during the submission and review of annual BMP progress data.

While specific requirements or decisions will be made by state and federal partners, the panel suggests the following for their consideration when constructing or evaluating an appropriate sampling, reporting and verification protocol for determining manure treatment system Level 3 transfer efficiencies:

- **There is no one-size-fits-all protocol for monitoring or sampling**. Sampling and testing of the influent (manure) and effluent (treated end products) should be conducted at a frequency appropriate to the size, scale, type(s) of treatment(s) and technologies being used.

- Sampling or monitoring data should be reported to the appropriate state/federal agency at least twice per year, preferably on a quarterly basis, even if only reported through NEIEN to the CBP once per year for annual progress runs.

Calculating the Level 3 Transfer Efficiencies

Lbs Removed/Year = Mass of N lost as gaseous emissions = NVE (see equation TT.2)

Note: if the system incorporates other feedstock(s) that represent 5% or more of the total mass of N in the system, then the reported transfer efficiency should be adjusted accordingly.

If the operator does not directly measure the amount of N removed from the treated manure in the form of gaseous emissions, then the operator can alternatively calculate a mass balance to determine their transfer efficiency.

N lost as gaseous emissions = (lbs-N of all inputs) – (sum of lbs-N remaining in all solid and liquid outputs)

The jurisdiction should use new or existing programs in order to maintain accurate records that may serve to enhance their reporting, tracking or verification efforts. This may include, but is not restricted to the following:

- The amount (in tons or lbs) of manure that is treated by the system.
- The type of livestock manure (or litter) being treated.
- Source location of the manure. If the treated manure is from another site (i.e. the system is not associated with one livestock operation), then the source county of the manure should also be recorded.
- End-use or fate of treated manure or other end-products. If the treated effluent or the end-product from the treatment process is transported to another county or outside the watershed, this information should also be recorded and could potentially be reported through other BMPs such as Manure Transport.
- An annual summary of the manure input and the fate/transport of the treated manure or any end products should be provided to the jurisdiction if the jurisdiction does not already collect or require this information.
- The dominant type of treatment technology or technologies utilized in the system, e.g. anaerobic digestion, pyrolysis, gasification, combustion, etc.

While the BMP could still be credited and simulated in the modeling tools without all of the above information, it will improve the accuracy of the simulation if the full set of information is available. Some information (amount of manure treated and location) is required for any system reported under the transfer efficiencies for Levels 1, 2 or 3 as described in Appendix A. If data elements are not reported available for Level 3 then the system will be simulated under the appropriate Level 2 or Level 1 BMP based on the provided available informationdata.

Note: The estimated nitrogen reductions associated with a given manure treatment system reported under Level 3 and calculated in the Chesapeake Bay Program Partnership environmental modeling tools will not necessarily be equal to credits generated (in pounds of TN) for water quality trading purposes. Water quality trading programs, whether intrastate or interstate, may have different calculation steps, retirement ratios, additionality requirements, or other factors that are not considered for this panel's purposes. This may be a source of confusion if attempts are made to compare the reductions credited for a treatment system in the CBP partnership modeling tools with any water quality trading credits associated with that same manure treatment system under a state's water quality trading program.

Table DD.1 summarizes applicable data collection or reporting requirements as described by Maryland, Pennsylvania and Virginia when contacted by the Panel Coordinator in the course of developing this report. The table is not intended to be a comprehensive description of applicable programs in the three states, as other programs may apply or be created in the future. Other jurisdictions not shown in Table DD.1 may also have their own programs or may create ones in the future. The table is provided as an informational guide to illustrate how, or if, a Level 3 transfer efficiency could be reported for a manure treatment system covered under the programs shown in Table DD.1.

Systems could be covered under one or more programs based on its source funding or regulatory requirements, so each system will need to be described in the jurisdiction's QAPP in order for the jurisdiction and EPA to determine its eligibility, on a case-by-case basis, for a Level 3 mass transfer efficiency. For these reasons it is likely that initially only a handful of systems will report Level 3 transfer efficiencies, but that number will likely grow if implementation incentives are accelerated. If the cumulative reductions for manure treatment systems reporting Level 3 treatment efficiencies becomes > 1% of a state's net nutrient reductions for one or more progress runs, the partnership should evaluate the reporting requirements for these systems and discuss whether improvements to the data collection, reporting and verification system are warranted.

11. Future research and management needs

The panel conducted a thorough review of published data on manure treatment technologies. The recommendations found in this report are as accurate as possible given the current state of science and technology. We fully expect this subject to be revisited by a future panel. To aid a future panel in its mission to improve upon our recommendations, the current panel suggests the scientific community consider the following recommendations for further research.

Farm-Scale Data Collection

Perhaps the greatest obstacle to accurately determine the performance of manure treatment technologies is the availability of data at the farm scale. Technologies developed in the laboratory do not necessarily perform at the same level when placed on farm in real conditions. We suggest coupling installation of new manure treatment technologies on farm to the applied research programs of land grant universities and the USDA Agriculture Research Service.

Nutrient Transformations

Mass balances of nutrients into and out of manure treatment systems should be performed as a part of all applied research projects on treatment technologies. These mass balances should also account for all forms of nutrients in waste streams, as well as, in fugitive losses. Data collection is most critical for determination of atmospheric losses of nitrogen in the form of N_2, NH_3, and NO_x.

Additional Categories of Technologies

A future panel will undoubtedly find additional categories of technology in use on farms in the Chesapeake Bay Watershed. Two categories of biological treatment that have already shown promise are liquid aerobic treatment of liquid manure and anaerobic treatment of solid manure. Liquid aerobic and anoxic technologies commonly used in domestic sewage treatment are making their way into the agricultural sector. Usually placed in conjunction with anaerobic digestion, these technologies further treat nutrients through nitrification-denitrification and biological phosphorus removal. Anaerobic composting and solid-state anaerobic digestion are two forms of treatment that may find use on farm, particularly to incorporate municipal, domestic, and food processing wastes into the manure handling system.

Additional Defined Technologies

Each section of this report contained a list of technologies that are available for manure treatment but are either not currently used in the Chesapeake Bay Watershed or farm-scale data is not available to make recommendations for nutrient transfer or transformation. More and better data may become available for future panels to expand the list of defined nutrient transfer efficiencies.

12. BMP Verification for manure treatment systems

Manure Treatment Technologies represents a new suite of BMPs for the CBP modeling tools starting with Phase 6. As such, the practice is not included in the jurisdiction's verification plans that were submitted to the CBP in late 2015.[3] As with all BMPs, the jurisdictions will be expected to document their verification protocols and procedures in their Quality Assurance Project Plan (QAPP) for manure treatment technologies that are reported to the CBP for nitrogen crediting reductions under the recommended BMPs. The jurisdictions will be able to do so after this expert panel recommendation report is approved by the CBP partnership following the BMP Protocol, and before the jurisdictions are able to start submitting these BMPs in the Phase 6 modeling tools. As the states consider how to verify manure treatment technologies and as they document those procedures in their QAPP, state partners should follow the existing Agriculture Workgroup's BMP Verification guidance.

The AgWG's current verification guidance breaks BMPs into three general categories: Visual Assessment BMPs (Single Year), Visual Assessment BMPs (Multi-Year), and Non-Visual Assessment BMPs. The complete AgWG guidance is quite extensive (79 pages long, including all tables and its own appendices) and is not restated in this section. The panel is not proposing any new or unique aspects of BMP verification for purposes of the BMPs described in this report. This section simply explains how the recommended BMPs correspond to the existing BMP verification guidance.

As described in Section 3 of this report, manure treatment is part of a larger manure management system that often involves multiple physical components (e.g., a compost bin, a digester, a screw press, a storage shed, etc.) which can be visually assessed over time. Manure treatment practices also incorporate non-visual components (e.g. manure transport) in addition to management plans or other documentation as needed under applicable state or federal agricultural permits and/or programs. Thus, manure treatment systems can reasonably be verified using elements of both the Non-Visual Assessment and Visual Assessment (Multi-Year) categories described by the AgWG.

Each state will determine the most appropriate methods for verifying the various MTT systems given their specific priorities, programs, needs, and capacity. For example, one state may lean more heavily on the Visual Assessment (Multi-Year) elements by leveraging existing site visits to farms to also verify that the composting facility meets applicable state or federal standards and specifications. Or, the state may determine that available records are detailed enough to provide sufficient verification through spot-checks. Ideally the state will leverage elements of both categories to verify that the physical treatment system is operating as intended, and that the data in their records are accurate and up-to-date.

To verify the default thermochemical and composting BMPs recommended in this report for nitrogen reduction credits in the Phase 6 CBWM (level 1), jurisdictions can reasonably follow the AgWG's guidance for Non-Visual Assessment BMPs. Verification for Non-Visual Assessment BMPs depend more on oversight and checks on records or documentation rather than visual assessment of a physical structure. The nitrogen reductions for default BMPs

[3] http://www.chesapeakebay.net/about/programs/bmp/additional_resources

described in this report can be verified following the AgWG's guidance for non-visual assessment BMPs since it is an annually reported BMP, and the most important criteria (i.e. type of treatment system, animal manure type treated, amount of manure that was treated) should be documented somewhere in records available to the applicable state agency. Given the close association between manure treatment and other CBP-approved BMPs (e.g., manure transport) the state agency can potentially verify the type and amount of manure that was treated via one of the thermochemical or composting systems described by the panel. If the state agency finds that even this basic information cannot be verified through its spot-checks or other annual BMP verification procedures described in its QAPP, then the BMP cannot satisfy the definitions and expected nitrogen reductions described in this report.

When the state agency has more detailed information available for both reporting and verification purposes, then they may be able to report the given system under the defined (level 2) category. By providing a separate category for the higher nitrogen reductions (defined, level 2), the panel provides a framework with additional built-in elements of BMP verification. If records available to the applicable state agency do not document the process factors described for that technology, then the given system should be reported under the corresponding default (level 1) BMP using the more basic information that is available. By assigning lower estimated reductions when only basic information is available, it is less likely that a reported treatment system will not provide the estimated nitrogen reductions developed by the panel. This reinforces the basis of BMP verification, i.e. that the reported practice is implemented and operating as intended. With more detailed information about the process factors, verified according to the AgWG's guidance, the partnership can have more confidence that the given manure treatment system is operating more effectively to remove nitrogen from the treated manure.

Manure treatment systems reported under the data driven (Level 3) category described in Section 10 demand more rigorous record-keeping and quality control of records to determine their reported nitrogen reductions. As discussed in Section 10, state and/or federal programs already exist that may require extensive data collection, sampling and reporting by the given farm or centralized manure treatment operation as part of a permitting or regulatory program.

For more information about the CBP Partnership's BMP Verification Framework

The full CBP partnership BMP Verification Framework is available online (scroll down to October 2014 Basinwide BMP Verification Framework Document):
http://www.chesapeakebay.net/about/programs/bmp/additional_resources

The current Agriculture Workgroup's BMP Verification Guidance is included in Appendix B of the full Framework Document. For the AgWG's guidance only, go here:
http://www.chesapeakebay.net/documents/Appendix%20B%20-Ag%20BMP%20Verification%20Guidance%20Final.pdf

APPENDICES

For convenience the appendices are provided as separate documents for duration of CBP partnership review. They will be combined into one document with the report following WQGIT approval.

Appendix A Technical Appendix for Scenario Builder
Appendix B Conformity with BMP Protocol
Appendix C Report from AgWG ad hoc subgroup on manure treatment technologies
Appendix D Minutes from the expert panel