APPROACHES TO NUTRIENT RECOVERY FROM DAIRY MANURE

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ACRONYMS

A	Ammonia Stripping
AD	Anaerobic Digestion
AS	Advanced Solids Separation
CAPEX	Capital Expense
CNG	Compressed Natural Gas
DAF	Dissolved Air Flotation
E	Evaporation Separation
M	Membrane Separation
MF	Microfiltration
MVC	Mechanical Vapor Compression
N	Nitrogen
NDN	Nitrification/Denitrification
NH_3	Ammonia
NH_4+	Ammonium
NR	Nutrient Recovery
NTU	Nephelometric Turbidity Unit
OPEX	Operational Expense
P	Phosphorus
PAM	Polyacrylamide
PS	Primary Separation
RO	Reverse Osmosis
SC	Struvite Crystallization
TSS	Total Suspended Solids
UF	Ultrafiltration

Manure and its associated nutrients can be valuable for crop production when it contributes to meeting plant nutrient needs. However, release of phosphorus (P), nitrogen (N), salts, and pathogens to the environment during manure management can contribute to numerous significant air and water quality concerns (Yorgey et al. 2014). As a result, dairies in many regions of the US are facing increased regulatory pressure (Rieck-Hinz et al. 2012). This is spurring government, industry, and farm interest in improving manure management and recovering manure nutrients through development and implementation of new technologies.

To support dairy, dairy-allied industry, and agency knowledge and decision-making, this paper provides an overview of the major nutrient recovery (NR) approaches now emerging or in use for recovery or removal of P, N, K, and other salts from dairy manure, particularly after anaerobic digestion (AD). Technologies, markets, and regulatory frameworks are evolving quickly and, as a result, this paper, its technology evaluations, associated performance, and cost estimates must be considered a time-sensitive snapshot of a changing industry.

Approach

This review summarizes technological approaches to NR appropriate for use with dairy manure, particularly, but not exclusively, dairy effluent from AD. AD treatment changes the form of manure in ways that may be beneficial for some NR approaches, but make other approaches more difficult. Systems combining both AD and NR provide a wealth of environmental benefits beyond NR, including renewable energy or fuel, and reduction in odor, pathogen, and greenhouse gas emissions (US-EPA 2004; US-EPA 2005). More information about the integration of NR and AD may be found in *The Dairy Manure Biorefinery* (Yorgey et al. in review) and additional publications referenced therein. Thermal renewable energy approaches such as combustion, pyrolysis, hydrothermal carbonization and gasification are also viable technical approaches to both NR and renewable energy production but are beyond the scope of this publication. Additional information on thermal applications can be found elsewhere (e.g., Cantrell et al. 2008, Pelaez-Samaniego et al. 2017).

Throughout this publication, the focus is on classes of approaches, and reference to specific technology providers has been avoided. The publication is therefore meant to provide a broad view of the industry and should not be used for individual technology purchase or investment decisions. For each of the more common technical approaches being used or considered by the dairy industry, this publication aims to summarize important indicators:

- approximate performance and capital (CAPEX) and operating and maintenance (OPEX) expenses,
- performance,
- co-product form and price, and
- impacts on manure management.

Information in this review is drawn from pilot and commercial demonstrations of NR technologies, with sources including the scientific literature, pilot reports, company literature, project feasibility studies, and interviews.

Making the data comparable required numerous assumptions, which are detailed in two sidebars: *Assumptions for Cost and Performance Indicators* and *Baseline Manure Management Scenario for Calculating Avoided Manure Management Costs*. These assumptions are important and should inform interpretation of the results.

Assumptions for Cost and Performance Indicators

The following assumptions have been used to facilitate discussion, comparison, and conclusions.

- Values for performance and costs are reported in units of cow^{-1} or cow^{-1} year^{-1}. Cow refers to a Holstein milking cow with specific as-produced manure and nutrient production rates summarized in ASABE (2005).
- While dairy systems can use a variety of manure handling approaches, the assumption is that manure is produced from a scrape system producing 35 gal cow^{-1} day^{-1} of combined manure, urine, and wash water (Harner et al. 2012).
- Newtrient, a US dairy industry company specializing in the value and sustainability of dairy manure, served as a reference point for obtaining industry data on CAPEX and OPEX. Wherever possible, multiple vendor quotes (3–5 vendors) within a treatment class of technologies were obtained to ascertain a range of costs. However, at times, a lack of commercial US facilities within a class of technology limited the number of accessible quotes. Peer-reviewed literature supplemented this and provided additional data points.
- All quotes and data points were from US dairies within a size range of 1,000 to 3,000 cows, with numbers scaled linearly to a base 1,500 cow dairy. No scaling factor is given in this paper for applying numbers and conclusions to smaller or larger operations.
- CAPEX refers to expenditures incurred in the simple purchase of the treatment technology and does not take into consideration either costs of money (i.e., interest and depreciation) or installation (i.e., engineering, permitting, protective buildings, as well as any excavation, groundwork, concrete pads, piping/utility connections, equalization pit, pumps/mixers that are peripheral to the core NR technology). The specifics of these costs will vary by technology, site, and financing choice; however, experience indicates that the cost can double or triple compared to the simple equipment purchase, and these considerations are very important for understanding the full cost (Eric Powell, personal communication).
- OPEX refers to expenditures incurred during the annual operation and maintenance of the equipment, specifically, the combined costs from required energy (i.e., electricity and heat), chemicals (i.e., acids and polymers), labor, and expected maintenance and parts replacement. Electricity has an assumed price of \$0.08 kWh^{-1}, while labor was estimated at \$35 hr^{-1} for simple walkthrough issues and \$75 hr^{-1} for repair. Where data was lacking for parts replacement, maintenance parts and labor were estimated at 4% of capital equipment excluding installation and cost of money.
- In many cases valuation of the exported product was difficult to assess as no established market presently exists; in such cases, best and conservative estimates were made. All quoted prices were for as-produced quality and considered no additional value-added upgrade (i.e., drying, pelletizing, and blending).

Manure Management Scenario for Calculating Avoided Manure Management Costs

One of the most important potential impacts of NR is that it can reduce a dairy's costs relating to nutrient management, but these costs vary substantially from dairy to dairy — and thus the avoided costs relating to implementation of NR technologies also vary. There is little available data relating to either the amounts of manure trucked on dairies or the costs of manure management, and while experience indicates significant variations exist across the US, the following scenario was used as a baseline to illustrate the potential for avoided manure management costs from NR:

- It was assumed that manure management was based on meeting crop needs for N.
- Of the total manure volume, 25% was assumed to be trucked to distant fields 5 miles from dairy while 75% was applied to nearby fields. To better understand the impact of this assumption, this number is also at times varied to consider a baseline with 35%, 50%, or 75% of manure hauled.
- Data from Hadrich et al. (2010) with adjustments to 2017 prices were used to determine costs. Prices are inclusive of long-term liquid storage, agitation, pumping, hauling, land application, and injection to soil.

Costs for the 5-mile distant trucking and nearby field scenarios were \$229 and \$100 cow^{-1} year^{-1}, respectively.

After the baseline scenario was constructed, the avoided costs were calculated for each technology reviewed in this publication. To do so, the following assumptions were made:

- When a technology allows for production of a stackable solid pile or concentrated liquid fertilizer, that product is assumed to be exportable from the farm gate, allowing for a removal of nutrients associated with the product. This nutrient export from the farm, alongside reductions in manure volume requiring land application, lead to corresponding reductions in manure management costs. This reduction, or avoided cost, for each class of technology is summarized in Table 1.
- This study assumes that approaches that can result in higher than 25% N removal can successfully satisfy both N and P management needs and allow for application to surrounding fields (at a cost of \$100 cow^{-1}) instead of hauling to a 5-mile distant fields (\$229 cow^{-1}).

Table 1. Avoided cost calculations for various technologies. In the discussion section of this publication, the performance of technology combinations are described as well as evaluated for scenarios that involve 35%, 50%, and 75% trucking in the baseline.

	Nitrogen Reduction[1]	Volume Reduction	Manure Hauled	Manure Applied Nearby	Avoided Cost
	%	%	cows	cows	(cow^{-1} year^{-1})
Baseline	-	-	375	1,125	-
Primary Solids	10%	10%	203	1,013	\$33.84
Advanced Solids*	35%	20%	0	900	\$72.25
Struvite	10%	---	225	1,125	\$22.90
NDN*	75%	---	0	1,125	\$57.25
Ammonia Stripping*	80%	---	0	1,125	\$57.25
Membranes*	95%	60%	0	450	\$102.25
Evaporation*	95%	60%	0	450	\$102.25

Nitrogen removed or recovered as products. Reductions are for the technologies identified − though in some cases, these technologies need primary treatment in order to work effectively.

*These approaches can result in higher than 25% N removal but for purposes of this scenario can only reduce the hauled manure from 25% to 0%.

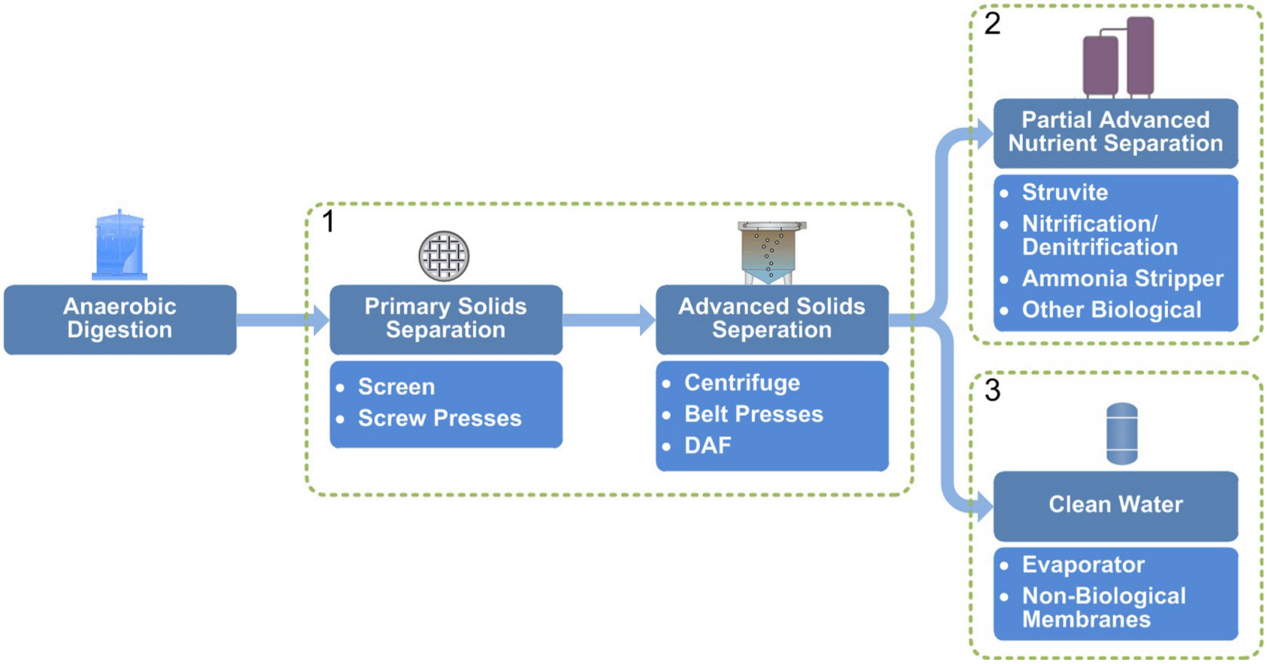

Figure 1. Up to three levels of treatment can be used to recover nutrients from dairy manure, which may be first treated with AD if desired. These levels include (1) separation of primary or advanced solids, (2) partial advanced nutrient separation and (3) clean water technologies producing water that can be re-used for various purposes.

Overview of Nutrient Recovery

Three general levels of nutrient recovery can be carried out. Figure 1 provides an overview of the three levels of treatment and indicates the organization of this review. Nutrient removal operations are generally implemented sequentially, as downstream systems (Levels 2 or 3) rely on earlier unit operations for removal of solids (Level 1) (Drosg et al. 2015). The result is an increasing level of complexity and cost as greater treatment occurs, but also an engineering approach that allows dairies and project developers to install technologies successively as time, funding, regulation, and markets warrant (Vaneeckhaute et al. 2017; Drosg et al. 2015).

The three levels of separation are:

Level 1: Solid Separation: The first level of treatment focuses on solids removal, producing a manure that is easier and less expensive to store, transport, and apply to fields. In the case of dairy manure and anaerobically digested manure, these initially separated solids are primarily of a coarse, large, and fibrous nature, containing only limited amounts of nutrients. These solids, with varying levels of treatment, can be used on-farm for bedding or sold as a soil or potting amendment (Jensen et al. 2016).

Advanced solids separation, focusing on suspended solids, yields an additional solid of a clay-like nature with smaller particle size and higher concentrations of nutrients, particularly P, and to a lesser degree, organic N (Hjorth et al. 2010). Beyond serving as a preliminary step to more advanced treatment, advanced solids separation produces a manure liquid that is more easily stored and applied to fields and can also be recycled as dilution water for a digester (Zeb et al. 2017).

Level 2: Partial Advanced Nutrient Separation: Partial advanced nutrient separation is usually preceded by one or more solids separation steps (Fuchs and Drosg 2013). During partial advanced nutrient separation, one or more physical, chemical, and biological approaches achieve higher levels of NR. In most cases, these approaches concentrate a fraction of the nutrients into a more transportable or saleable product while leaving a liquid effluent of nearly the same volume that still requires field application. However, because this effluent has markedly lower concentrations of nutrients, it can be applied at higher rates to nearby land, leading to reductions in transport and application costs — while facilitating dairy nutrient management plans.

Level 3: Clean Water: In contrast to partial advanced nutrient separation that does not appreciably reduce the volume of effluent, clean water technologies significantly reduce the volume of manure that needs to be stored and field-applied by separating the manure liquid into two fractions. The first is a highly filtered water fraction that could have other uses beyond field application, such as for process water, animal drinking water, irrigation, and discharge. While various levels of treatment can be achieved, for the purposes of this paper, the target is assumed to be a relatively high treatment standard, achieving ≤ 5 Nephelometric Turbidity Unit (NTU) turbidity, 30 mg L^{-1} total suspended solids (TSS), and 15 mg L^{-1} ammonia-N. The second is a concentrate stream that is normally field applied, but with a substantially reduced volume compared to the effluent left after partially advanced nutrient separation.

Solids Separation (Level 1)

Primary Solids Separation

The most common current commercial-scale NR approach utilized on both AD and non-AD dairies involves primary solids separation. This approach uses various types of screens and screw presses to separate out large particles and easily settled fibrous solids. Typical primary screening operations can remove between 20–40% of total solids in the manure, yielding 9–12 cubic yards (yd^3) cow^{-1} year^{-1} of screened and pressed wet fiber (Table 2) (Jensen et al. 2016). Choice of approach as well as removal performance is dependent upon many factors including location, thickness of manure liquid, preferred dry matter content of product, and maintenance track record. Because the fibrous solids have high carbon content and relatively low N and P content, primary screening typically removes only small amounts of nutrients (Jensen et al. 2016).

Depending on complexity, primary separation costs are on the order of \$23–55 cow^{-1} in CAPEX with \$8–16 cow^{-1} year^{-1} in OPEX. OPEX, which vary primarily based on level of separation performance and quality of produced product, are incurred from items such as regular wash downs or periodic acid scrubs to remove accumulated salts and precipitates, replacement parts, electricity, and transportation of product.

Separated fibrous solids from AD digestate can be used on farm as bedding, either directly or with additional downstream compost treatment (Figure 2, left and center). In this case, it has financial value in the form of reduced or eliminated costs for purchasing sawdust, straw, or other bedding materials.Typical revenues calculated from offset savings are on the order of \$8–10 wet yd^{-3} (Jensen et al. 2016). Farms generally can use about 50% of the produced fiber internally, while the remainder can be sold as bedding to nearby dairies without a digester or processed into other value-added products (Pelaez-Samaniego et al. 2017). One emerging value-added use is as a peat replacement in the soil amendment or horticulture industries (Figure 2, right) (Goldstein 2014; Hummel et al. 2014). Discussions with this nascent industry suggest that dairy AD operations can achieve approximately \$10–17 yd^{-3} for bulk quantities of AD or composted fiber, with wholesalers paying transportation costs (Jensen et al. 2016). For the purposes of this study, the valuation for the one-half of fibrous solids sold off farm is assumed to be \$10 yd^{-3}, which converts to \$50 cow^{-1} year^{-1}. More detailed information on AD fiber is provided in Digested Fiber Solids: Developing Technologies and Trends for Adding Value (Jensen et al. 2016).

Table 2. Summary of primary solids separation costs, performance, and revenues

Expenses		Partitioning			Revenue/Avoided Costs		
CAPEX [a]	OPEX [b]	Nutrients [c]		Volume [d]	Product Yield [e]	Product Revenue	Avoided Costs
cow^{-1}	cow^{-1} cow^{-1}	% N	% P	%	yd^3 cow^{-1} year^{-1}	cow^{-1} year^{-1}	cow^{-1} year^{-1}
\$23-55	\$8-16	10-20	10-20	10	9-12	\$50	\$34

[a] Newtrient 2017; [b,c,d,e] Jensen et al. 2016; and sources cited therein.

Figure 2. Close-up of separated AD fiber (left). Two major uses include as animal bedding (center) and, as an ingredient in retail soil amendment (right). Photos: Craig Frear, DVO Inc., and Rita Hummel, WSU (left to right).

Advanced Solids Separation

After primary solids separation, additional treatment of the liquid stream can be used to achieve higher levels of suspended solids and nutrient removal, particularly P (Table 3). The key feature of advanced solids separation approaches is that they aim to achieve separation of very fine, suspended solids (>90% TSS removal). Importantly, this also removes a significant amount of P, as research has shown a preferential association between these small suspended solids and P, as well as organic N (Chapuis-Lardy et al. 2004; Gungor and Karthikeyan 2008). This process can be used on both AD and non-AD manure, although the additional solids and complex organics in non-digested manure can lead to cost increases.

Three of the more common approaches to advanced solids removal are centrifuges, flocculation systems, and pressure membrane systems. Centrifuges utilize gravitational forces and can be used with or without flocculants or polymers, although due to concerns related to polymer efficiencies and costs, they typically operate solely on gravitational force (Figure 3).

Flocculation systems use a variety of approaches such as fine mesh vertical screens, belt presses, and dissolved air flotation (DAF). However, all rely on the principle of adding polymers, flocculants, or binders, alone or in combination with each other to induce flocculation of suspended solids and their subsequent separation and dewatering (Figure 3). As these chemicals are added, small particles form, followed by larger aggregates, and finally visible floc particles which, depending on the specific system, settle or rise rapidly. Because of pressure to reduce costs, most systems utilize solely polymers with specific charge and molecular weights. Among these, polyacrylamide (PAM) is the most common — although emerging regulations on PAM use and the desire for organic certification are stimulating concerted efforts regarding use of natural polymers (Mehta et al. 2015).

Ultrafiltration (UF) offers a membrane-based approach to fine solids separation. The UF membrane acts as a barrier that precludes passage of suspended solids while allowing water and dissolved solids to permeate. Tubular membrane products are most commonly employed due to the high concentration of suspended solids found in dairy manure. To avoid plugging concerns, coarse fiber is removed prior to the UF membrane. Systems are generally designed in a cross-flow configuration to minimize fouling at the membrane wall; however, though this configuration is effective for separating suspended solids, there is a significant electrical demand (Safferman et al. 2017). When treating dairy manure with ultrafiltration, a pilot-scale system produced a concentrated stream containing 96% of the phosphorus and 88% of the organic nitrogen, whereas the dilute stream was devoid of suspended solids and contained the dissolved constituents including ammonia/ammonium nitrogen and potassium (Wallace et al. 2015).

Table 3. Summary of advanced solids separation costs, performance, and revenues

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[a,b] Newtrient 2017; [c,d] Hjorth et al. 2010; [e] Frear 2017
*Quoted ranges for centrifuge and polymer/flocculation process. Ultrafiltration considerably higher and more on par with discussion in later membrane section.

Choice among the varying options can be influenced by CAPEX and OPEX, product form desired, potential for organic certification of solid product, maintenance track record, specific farm needs related to nutrient management, and whether the farm would like to further treat the produced liquid. In general, centrifuge produces a consistent and dry product with no requirement for chemical/polymer addition. However, without a chemical or polymer, the nutrient removal efficiencies are typically in the lower end of the range, and users have reported some concerns related to high maintenance costs. Flocculation systems generally perform at the higher end of the range of nutrient removal with lower electrical and maintenance costs, though the added chemicals or polymers raise costs and impact product quality and use (Newtrient 2017). Ultrafiltration has comparatively higher costs and concerns related to CAPEX, OPEX, and maintenance, while producing a liquid stream of higher quality and more suitable for clean water treatment.

Little market information is available regarding the value of the fine solids that are produced, as installation of such technologies is limited so far, and markets immature. At extremely large scales, the product is now just beginning to be marketed after extensive post-treatment with driers, pelletizers, and mineral additions (Midwestern Bioag 2017). However, at moderate scales, the product is usually not actively post-treated beyond open-air drying or in some cases composting. While quite concentrated in valuable macro- and micro-nutrients, there is no current estimated value for the product. The solids are wet and difficult to spread, there are concerns about the potential presence of polymers, and there is a lack of existing markets. Additional research, and development of mature markets, may allow for future growth in revenue potential.

Figure 3. From left to right, top; belt press polymer/flocculation system, decanting centrifuge (photo GEA), DAF polymer/flocculation system. From left to right, bottom; as-produced solids from three respective technologies, and sample of tea water effluent from the DAF (photo DVO, Inc.). Photos: Regenis except as otherwise noted.

Partial Advanced Nutrient Separation (Level 2)

Partial advanced nutrient separation technologies treat effluent from the solids separation systems already discussed. Most of these technologies focus on N remaining in the manure, except for struvite crystallization that focuses on P removal. These approaches are distinguished from clean water technologies because they do not appreciably reduce the volume of liquid or the amount of salts.

Understanding the form of N in dairy manure, and how that form is transformed during AD, is important to understanding the technologies that are being proposed for N recovery. Unprocessed manure contains approximately half of its N in organic form and half in ammonia while the AD and solids separation processes remove much of the organic N or convert it to ammonia N (Holly et al. 2017). Advanced efforts aimed at N therefore are preferentially designed to treat ammonia.

Struvite Crystallization

Struvite crystallization (Table 4) has been effectively used within municipal wastewater treatment and for treating swine manure (Vaneeckhaute et al. 2017; Bowers and Westerman 2005). However, the calcium-P precipitates present in dairy manure can disrupt struvite crystallization (Le Corre et al. 2007), and therefore modifications of the struvite process have been necessary to attain high levels of removal efficiency for dairy manure (~75% P removal with modification) (Zhang et al. 2010).

A modified struvite crystallization process has been commercialized on a 1,200 cow US dairy (Figure 4) producing struvite crystals while removing approximately 75% and 10% of total P and N, respectively (Keith Bowers, personal communication).

Figure 4: Struvite crystallizer and product (inset). Photos: MultiForm Harvest.

In the case of this installation, only primary solids separation was completed prior to struvite crystallization due to the very dilute manure liquid produced by the dairy’s flush handling system. Thus, struvite crystallization has the potential of acting as a primary P recovery system when using dilute manure or manure digestate, but also as a polishing agent for P when used following advanced solids separation.

Table 4. Summary of struvite crystallization costs, performance, and revenues

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[a,b,c,d,e] Keith Bowers, personal communication

Struvite is roughly 10%, 6%, and 13% by mass magnesium, N and P in the form of $MgNH_4PO_4 \cdot 6H_2O$. This slow release fertilizer of uniform, dry crystals, is concentrated in nutrients and is quite suitable for application with existing fertilizer equipment and, unlike other produced solids, little to no post-production treatment is needed (Collins et al. 2016). Quoted price points for the struvite crystals are \$150 ton^{-1} in their present form (Keith Bowers, personal communication), which also aligns with some of the price points discussed in Vaneeckhaute et al. (2017).

Nitrification/Denitrification

Within the municipal sector, ammonia N is reduced via biological nitrification/denitrification (NDN). This process traditionally consists of two stages: aerobic nitrification, carried out by microbes that require oxygen and synthesize their own food, and anaerobic heterotrophic denitrification, carried out by microbes that live in the absence of oxygen and consume food from their environment (Zhu et al. 2008; Sun et al. 2010). Traditional NDN has struggled with concerns related to cost that result from known limits in slow nitrification, sensitivity to oxygen limitation, overloading of ammonium and solids concentrations, a requirement for readily-available organic carbon, and a need for multiple, integrated reactors (Desloover et al. 2012). The municipal sector has been largely successful in addressing these concerns by adopting novel modified NDN processes, but to date, these modified processes have not been transferred to the animal sector (Kang et al. 2008). Dairy manure and manure digestate are problematic to NDN due to their high concentrations of ammonium-N and suspended solids, even after solids separation. In the case of digested manure, the low availability of readily-degradable carbon is also of concern. Lack of available carbon is not just a concern in maintenance/cost of the denitrification step, but in control of unwanted nitrous oxide emissions, which have been linked to insufficient available carbon (Kampschreur et al. 2009).

Accordingly, application of NDN systems has been quite limited in the animal sector, with existing systems utilizing the conventional approach, and applied mostly to swine slurries (Flotats et al. 2011). Recently, new approaches have been introduced. These approaches use dedicated reactors, but with modifications to flow patterns so that a single reactor with reduced electrical and aeration inputs can be utilized. Despite the modifications, costs remain relatively high, impacting adoption (Choperena 2010; Newtrient 2017).

More, but still limited interest, has been shown in systems that use traditional NDN, but reduce costs through use of existing long-term liquid storage basins re-purposed for use as NDN tanks (Doug VanOrnum, personal communication).

A design receiving the most attention and some degree of adoption is a vermifiltration trickling filter (Figure 5; SUSCON 2017). These systems are passive aerobic bio-reactors, which contain layers of worms, castings, wood shavings, and other porous media through which the manure liquid flows are treated in a relatively short hydraulic retention time (PGE 2014).

Figure 5. Vermifiltration system. Photo: Biofiltro.

Performance evaluations for the vermifiltration trickling filter show relatively low operating and energy costs, albeit requiring regular attention for monitoring the system, while significantly reducing N concentrations in the effluent. Analysis from a multi-disciplinary team of scientists at a California dairy, have shown reductions via the vermifiltration system of 65% of total N, and 42% electro-conductivity (EC). Analysis of the data and microbiome points to a NDN process as a means for the reduction, although the definitive role of the worms in the NDN process is still unclear (SUSCON 2017). SUSCON (2017) reports value added production of approximately 0.4 yd^3 casting cow^{-1} year^{-1} and 1.3 lb worm cow^{-1} year^{-1}, with revenue for the castings of \$12 cow^{-1} year^{-1} (\$30 yd^{-3}). As most NDN in this class do not generate castings, and in all forms the reactive N is released as nonreactive N gas, the product revenue in the NDN summary table is assumed to be zero.

Table 5. Summary of nitrification denitrification (NDN) costs, performance, and revenues

Expenses		Partitioning			Revenue/Avoided Costs		
CAPEX [a]	OPEX [b]	Nutrients [c]		Volume [d]	Product Yield [e]	Product Revenue	Avoided Costs
cow^{-1}	$\text{cow}^{-1}\,\text{year}^{-1}$	% N	% P	%	$\text{yd}^3\,\text{cow}^{-1}\,\text{year}^{-1}$	$\text{cow}^{-1}\,\text{year}^{-1}$	$\text{cow}^{-1}\,\text{year}^{-1}$
$212-502	$15-50	60-90	20-50*	NA	NA	$0	$57

[a] Newtrient 2017; [b] Newtrient 2017; SUSCON 2017; Doug VanOrnum, personal communication; [c,d] Newtrient 2017; SUSCON 2017; Doug VanOrnum, personal communication

* NDN systems also sequester P within the separated biomass, thus acting as a partial biological P removal system, although greater process and biological control (selection for P-accumulating organisms can accentuate the P removal (Ahn et al. 2007).

From a sustainability perspective, loss of reactive N is not ideal, given the high energy and greenhouse gas costs associated with the Haber-Bosch process for conversion of atmospheric N back into reactive N fertilizer. However, on the upside, NDN does not require the complex and costly implementation of storage, drying, transportation, and marketing systems for the sale of fertilizer products, a considerable barrier for manure-derived fertilizers.

Ammonia Stripping

Ammonia stripping (Table 6) rests on the principle that a rise in pH or temperature (or both) can shift the ammonium ion (NH_4^+) equilibrium towards gaseous ammonia (NH_3), allowing for its removal and collection from the manure (Jiang et al. 2014).

The process recovers ammonia-N as an aqua solution (ammonia water) or as an ammonium salt fertilizer (Figure 6). Achievement of the appropriate temperature and pH can be accomplished through a variety of techniques including air, carbon dioxide air, vacuum, membrane, and steam stripping (Eekert et al. 2012). Use of ammonia stripping for manures is particularly intriguing in concert with AD as ammonia concentrations within the effluent are relatively high and the needed thermal energy can be provided from waste heat during the combined heat and power generation (Jiang et al. 2014). In addition, AD produces a liquid somewhat elevated in pH, dissolved carbon dioxide, and carbonate and bicarbonate species, conditions that can benefit both carbon dioxide stripping and ammonia stripping (Zhao et al. 2015).

Figure 6. Non-chemical carbon dioxide and ammonia air stripper (left) and media tower ammonia air stripping (right). Photos: DVO Incorporated and Byosis.

Table 6. Summary of ammonia stripping costs, performance, and revenues

Expenses		Partitioning			Revenue/Avoided Costs		
CAPEX [a]	OPEX [b]	Nutrients [c]		Volume [d]	Product Yield [e]	Product Revenue	Avoided Costs
cow $^{-1}$	cow $^{-1}$ year $^{-1}$	% N	% P	%	ton cow $^{-1}$ year $^{-1}$	cow $^{-1}$ year $^{-1}$	cow $^{-1}$ year $^{-1}$
$300-500	$50-100	72-85	0	NA	0.48	$60	$57

[a] Vaneeckhaute et al. 2017; Newtrient 2017; Bolzonella et al. 2017; [b] Newtrient 2017; Vaneeckhaute et al. 2017; Eric Powell, personal communication; [c,d] Newtrient 2017; Vaneeckhaute et al. 2017; [e] mass balance from 1100 ppm ammonium-N concentration and 80% recovery.

Unfortunately, traditional ammonia stripping has concerns that have limited its use for treatment of manures, though investigation of modified processes continues. To date, costs have often been prohibitive, especially for dilute manures and manure AD effluents containing high alkalinity, due to the need for alkali chemical to elevate the pH, or heat to increase the temperature (~10–11 kg lime m^{-3} at a cost of $1 m^{-3}; Jiang et al. 2104). Non-chemical or carbon dioxide stripping as well as advanced solids removal can partially overcome these alkalinity issues and reduce the chemical cost, but the electrical requirement for aeration can still be considerable (0.02–0.07 kW cow^{-1}) (Zhao et al. 2015; Vaneeckhaute et al. 2017).

While excess thermal energy is available at many AD projects (although notably not available at emerging compressed natural gas (CNG) facilities), ammonia steam stripping requires thermal inputs that are often above what is available from AD projects, thus requiring the purchase of expensive outside energy inputs (Liao et al. 1995). Additionally, traditional stripping tower systems utilizing packing media or tray towers are prone to solids interception from the AD effluent, although use of advanced solids treated manure can totally or partially address these concerns (Drosg et al. 2015). Non-packing tower approaches using complete-mix or plug-flow systems may also resolve this concern and are now of interest (Bauermeister et al. 2009; Zhao et al. 2015).

Air stripping systems produce a dilute ammonia gas stream that has air, carbon dioxide, moisture contaminants, and that requires subsequent treatment with acid towers to produce concentrated ammonium salt fertilizers. This adds considerable downstream cost usually for concentrated sulfuric acid (alternatives include phosphoric acid, nitric acid, or gypsum.) Steam and membrane stripping allow for a more concentrated stream capable of producing an aqua solution, reducing downstream acid costs, but produce a less desirable and less stable product.

Cost analysis for ammonia stripping systems is difficult given the wide variety of approaches and limited data available, with some assumptions made using best available data for practical manure systems (Vaneeckhaute et al. 2017). Mass analysis alongside typical ammonia-N concentrations in digested dairy manure and assumed performance of 80% ammonia removal, can produce a product yield of 0.18 dry ton of ammonium sulfate (21% N dry weight) cow^{-1} year^{-1}, which typically is in dilute, solution form (38% concentrate or ~8% N) with a mass of 0.48 wet ton cow^{-1} year^{-1}. Quoted price points for the ammonium sulfate solution are in the range of $100–150 wet ton^{-1} (Vaneeckhaute et al. 2017).

Clean Water (Level 3)

Treatment of dairy manure to produce “clean water” suitable for re-use as animal drinking water, process water, or for discharge, is receiving interest, as this approach would significantly reduce the volume of dairy manure requiring storage and field application. This is of interest to dairy regions that are presently incurring high costs in hauling a significant fraction of their manure liquid long-distance to meet nutrient management plans. Additionally, some dairy regions are experiencing changing precipitation patterns that are placing burdens on existing long-term liquid storage infrastructure — and in this case reductions in volume could potentially be used to avoid the need for new construction. Here, we discuss two approaches for achieving clean water: membrane and evaporation systems.

Membranes

In general, membrane filtration (Table 7) removes particulate matter from liquid waste by forcing the liquid through a semi-permeable film (membrane) with a driving force (Mulder 2000).

The driving force can be a difference in pressure, concentration, temperature or electric potential, with pressure-driven systems most common. The separation range of membrane processes is categorized by particle size. In general *Microfiltration (MF)* has pore sizes in the range of 0.1 to 1 micron, *Ultrafiltration (UF)* has pore sizes in the range of 0.1 to 0.001 micron, removing high molecular-weight substances, colloidal materials, and organic and inorganic polymeric molecules; and *Reverse osmosis (RO)* has a pore size around 0.0001 microns and removes dissolved solids and salts. The choice or sequence and combination of membranes is specific to vendors as well as location, desired need, and end-production specifications.

Membranes have been used commercially for digested and raw dairy manure since the early 2000s with gradual growth in commercial adoption both in Europe and the US, although the application is still quite limited, impacted by high CAPEX and OPEX as well as instances of troublesome performance (Figure 7) (Velthof 2011; Drosg et al. 2015; Newtrient 2017). Effective solids removal using advanced solids separation prior to membrane treatment has been identified as an important prerequisite for success.

When installed systems have not met promised performance or cost metrics, ineffective pretreatment for solids is often the point of failure, as it leads to repeated and costly fouling of membranes as well as ever increasing electrical demand due to pressure placed on the membranes (Drosg et al. 2015; Peter-Varbanets et al. 2009).

Membrane systems are usually used to produce a permeate or ‘clean water’ as well as a reject stream or concentrate. The proportion of overall manure converted to clean water and its quality is dependent upon the types of membranes and number of membrane cycles as well as addition of supplementary systems such as activated carbon (Drosg et al. 2015). Many operations utilize at least three RO steps to achieve water quality sufficient for discharge (Drosg et al. 2015). Even with this type of sequential treatment, membrane manure systems often only achieve 50–70% permeate or clean water production (Drosg et al. 2015; Hoop et al. 2011; Chiumenti et al. 2013a). Meanwhile, the remaining concentrate is still in need of field application and carries with it the original bulk of input nutrients. This concentrate is unlikely to be sold off-farm given that it is quite dilute, has non-ideal salt-to-N ratios, and may also contain pathogens.

Table 7. Summary of membranes costs, performance, and revenues

Expenses		Partitioning			Revenue/Avoided Costs		
CAPEX [a]	OPEX [b]	Nutrients [c]		Volume [d]	Product Yield [e]	Product Revenue	Avoided Costs
cow $^{-1}$	cow $^{-1}$ year $^{-1}$	% N	% P	%	ton cow $^{-1}$ year $^{-1}$	cow $^{-1}$ year $^{-1}$	cow $^{-1}$ year $^{-1}$
$500-750	$100-200	95	95	50-70	11.6	$0	$102

[a,b] Newtrient 2017; Bolzonella et al. 2017; [c,d] Chiumenti et al. 2013a; [e] Chiumenti et al. 2013b. Performance data adapted to this dairy manure study.

Figure 7. Membrane system. Photo: Regenis.

For the purposes of Table 7, a complete RO system aimed at highly filtered water is assumed, with less intensive membrane treatment with micro or ultra-filtration systems evaluated as an advanced solids separation system. Chiumenti et al. (2013a) data, adapted to the assumed flows and concentration of this study, yields a concentrate flow of 11.6 ton cow^{-1} year^{-1} of 4.8% total solids and N and potassium dry values of 11.6% and 10.7%, respectively. While the concentrate in this system is reduced in volume, producing a more concentrated form of fertilizer and, therefore, potentially of greater value (Hoop et al. (2011) quotes European pricing for RO concentrate at \$125–150 cow^{-1} year^{-1}, excluding transportation), it is still relatively dilute and thus faced with many of the existing concerns regarding valuation of manure. For this reason, the value of the concentrate is assumed to be zero, with dairies still required to pay for transportation for disposal.

Evaporation

Evaporative systems are another option for volume reduction and subsequent concentration of the nutrients (Table 8). These systems use multi-stage thermal and electrical inputs under vacuum to distill and then condense clean water. As with membrane systems, the process produces a ‘clean water’ and a concentrate, in this case, typically with total solids concentration of 12–25% (Drosg et al. 2015; Vondra et al. in press). Acid treatment is often utilized to depress pH before evaporation to maintain the bulk of ammonia N as ammonium ion in solution (Figure 8). Evaporative systems can achieve similar results to that of membranes, reducing overall manure volume by 40–75% and producing both the concentrate and the condensed water (Heidler 2005). For those preferring the highly filtered water suitable for discharge, inclusion of an additional RO membrane treatment might be required to upgrade the quality of the recovered process water (Drosg et al. 2015). Primary solids separation is a pre-requisite for evaporation, however, not as high a degree of fine solids interception is required as compared to membranes.

Unless mechanical vapor compression (MVC) systems are utilized, typical approaches require both a thermal and electrical input. For AD digestate, there is the potential to offset at least some thermal costs with available waste heat from the digester combined heat and power engines (Vondra et al. 2017). In the case of AD digesting only dairy manure in typical Midwest US climates, the degree of offset is only minimal (~10% reduction in thermal need), however this can be significantly increased (to ~50%) for AD projects practicing a high degree of co-digestion with off-farm organics.

Table 8. Summary of evaporation costs, performance, and revenues

Expenses		Partitioning			Revenue/Avoided Costs		
CAPEX [a]	OPEX [b]	Nutrients [c]		Volume [d]	Product Yield [e]	Product Revenue	Avoided Costs
cow $^{-1}$	cow $^{-1}$ year $^{-1}$	% N	% P	%	ton cow $^{-1}$ year $^{-1}$	cow $^{-1}$ year $^{-1}$	cow $^{-1}$ year $^{-1}$
\$400-900	\$250-360	95	95	40-75	12.1	\$0	\$102

[a] Drosg et al. 2015; Chiumenti et al. 2013b; Hoop at al. 2010; Jeff Graff, personal communication; [b] Vondra et al. 2107; [c,d] Hoop at al. 2010; [e] Drosg et al. 2015. Performance applied to scale and parameters used in this dairy manure study.

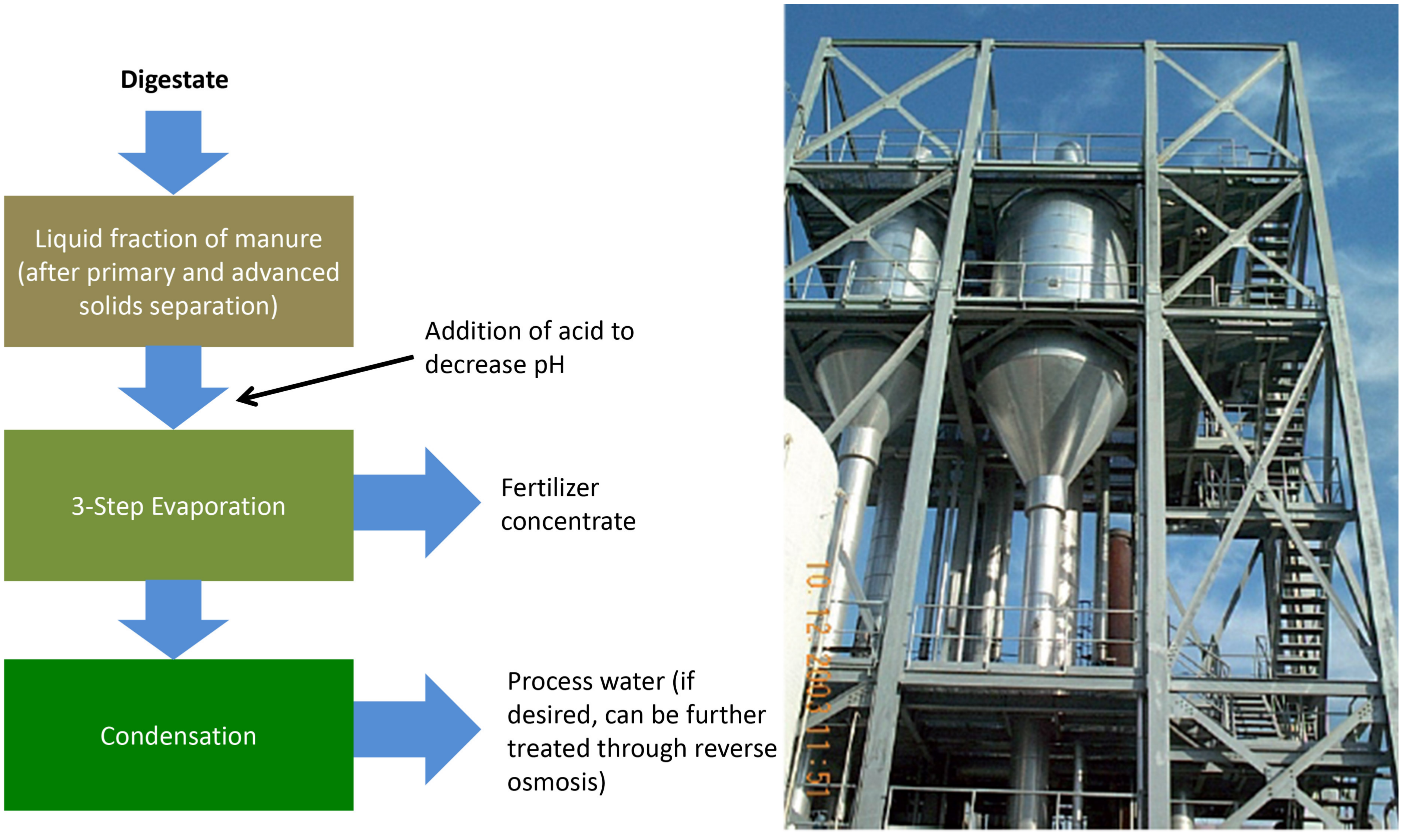

Figure 8. Typical evaporation process for purified water (left), and vacuum evaporator, Catalonia, Spain (right). Figures: left by Liz Allen (adapted from Fuchs and Drosg, 2013), right from SARGA 2015.

Recently, pilot research has investigated a hybrid combination of MVC evaporators with an MVC-driven dryer to achieve increased dry matter content of the product, beyond the 12–25% range and as high as ~90%, levels suitable for pelletization and sales as a solid product. In addition to this solid product and the condensed clean water, this system produces an aqua-ammonia solution, however, additional deployment and evaluation is needed to assess the performance of this system (Jeff Graff, personal communications).

Systems

In practice, it is likely that one or more of the discussed technologies will be used in sequence, with each system based on an overall approach that meets the dairy's manure treatment and business goals. Figure 9 details some of the more common systems that could arise from technologies discussed in this review. Depending on the outputs, NR would be followed by fertilizer/solids handling for recovered products, and bulk long-term storage and field application for remaining liquid or concentrate.

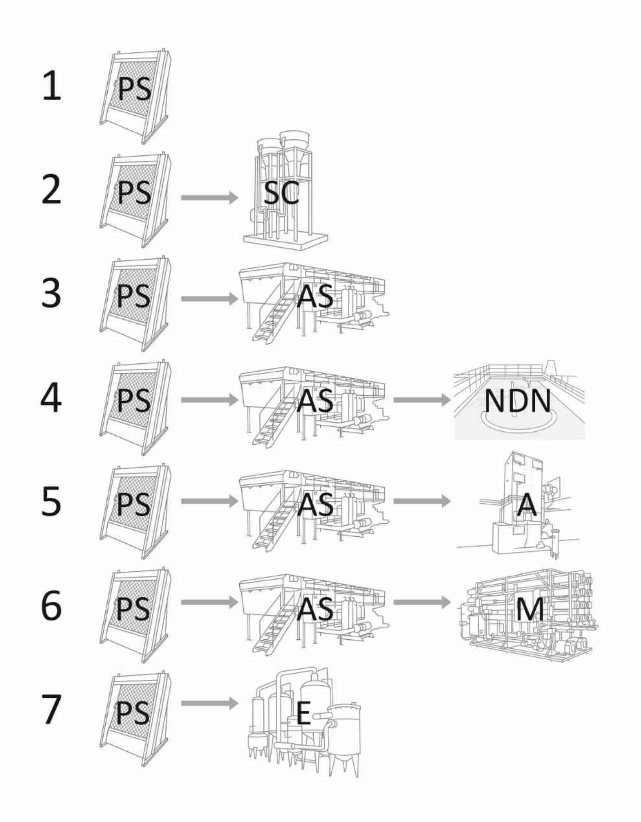

Figure 9. Select technology scenarios (PS=primary separation; SC=struvite crystallization; AS=advanced solids separation; NDN=nitrification/denitrification; A=ammonia stripping; M=membrane separation; and E=evaporation separation (drawings courtesy Newtrient))

Discussion

Using the systems described in Figure 9, cost, revenue, and performance was calculated using simple addition of individual technology CAPEX, OPEX, product costs/revenue, and serial addition of individual technology nutrient and volume reductions. The relative costs, revenues and avoided manure management costs of a range of technological approaches, is summarized in Figures 10 and 11. The reader is strongly cautioned against drawing conclusions about whether technology systems are financially feasible based on the data in these figures. Specifically, the cost estimations do not represent true finance and installed costs. Beyond this, true costs on a dairy would be strongly influenced by many site-specific factors relating to the type of baseline manure management, the scale of the dairy operation, the volume and characteristics of manure needing treatment, and the specifics of the N, P, or volume concerns that need to be addressed.

In support of this caution, conversations with dairies and industry providers indicate that NR is perhaps better seen as a required cost of doing business rather than as an add-on technology with a stand-alone financial payback to the dairy. As such, even when they would provide nutrient management benefits, financing and operating NR technology systems could be difficult for dairy enterprises already under financial pressure from low milk prices in recent years.

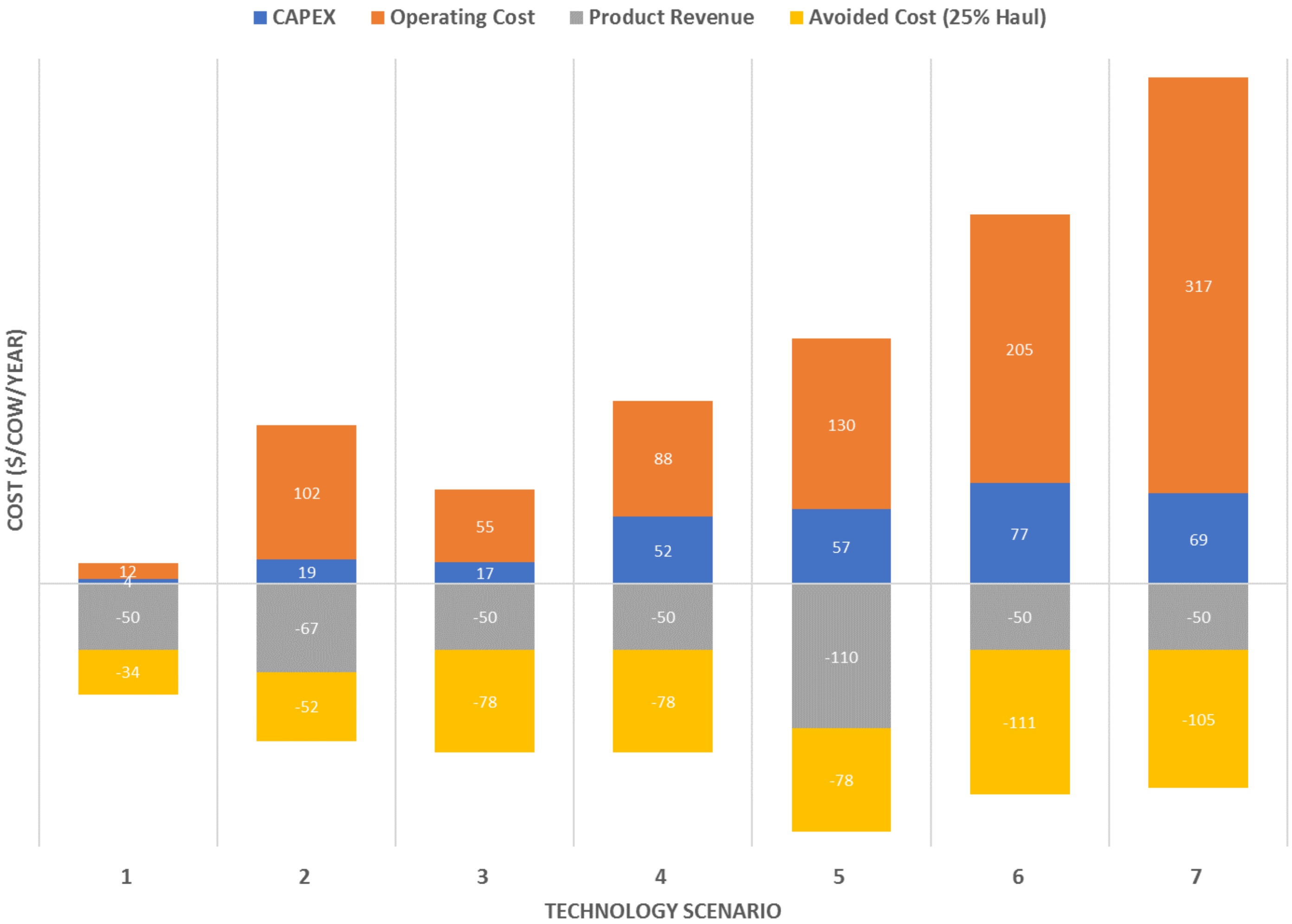

Figure 10. Comparison of capital expenses (CAPEX) and operating costs (OPEX) as well as product revenue and avoided manure management costs by technology scenario, as defined in Figure 9. Initial AD treatment is assumed, and NR is assumed to be followed by bulk liquid long-term storage and fertilizer/solids handling. Important additional assumptions detailed in the sidebars ***Assumptions for Cost and Performance Indicators and Baseline Manure Management Scenario for Calculating Avoided Manure Management Costs***. Among the most important, no consideration was made for installation or financing costs (interest and depreciation), and avoided manure management costs assumed that 25% of manure is hauled prior to land application. In this figure, CAPEX is normalized to a common \$ cow^{-1} year^{-1} value by dividing total \$ cow^{-1} costs against an assumed 10-year payback.

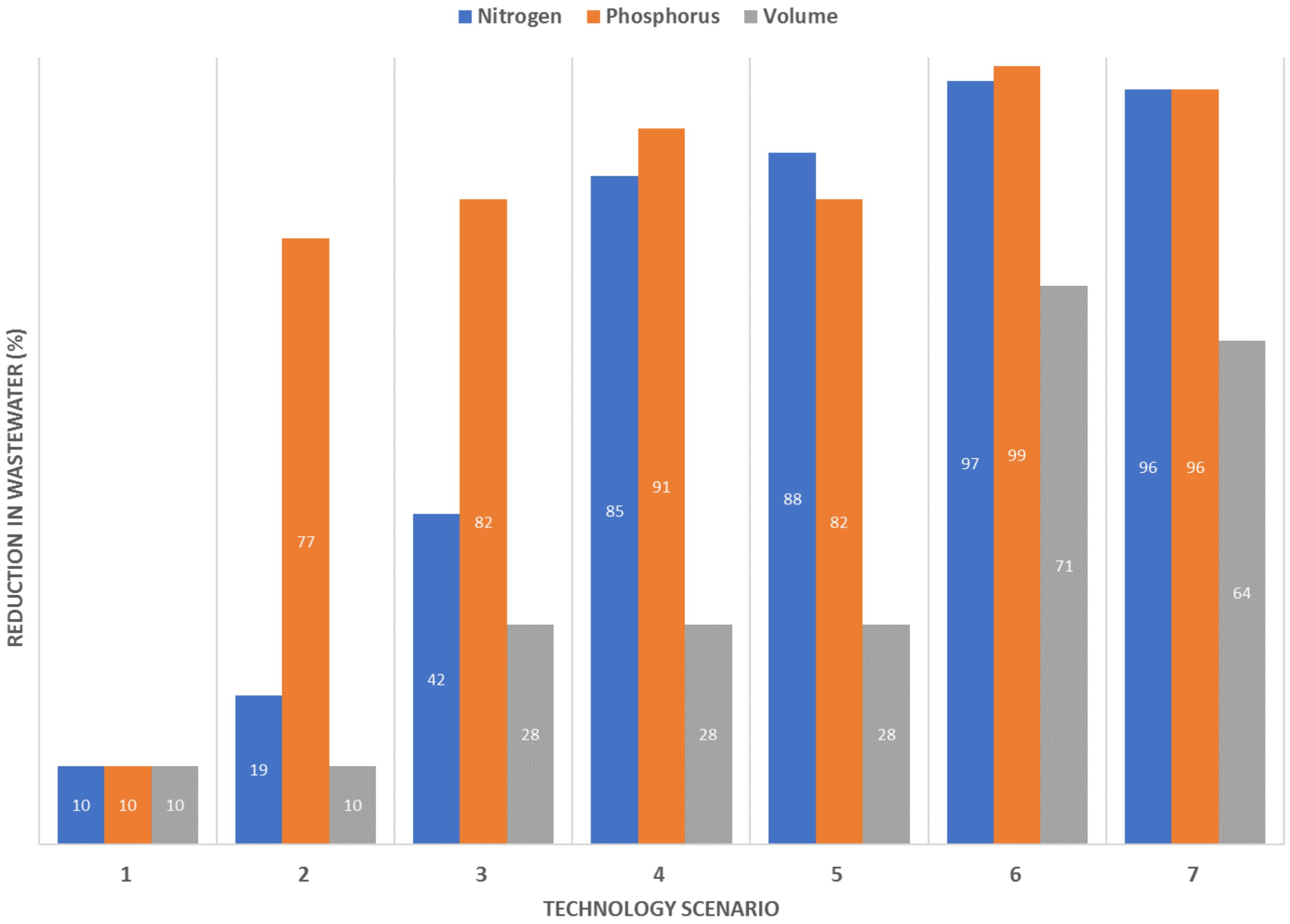

Figure 11. Comparison of N, P, and volume reductions achieved by each technology scenario. Technological scenarios are detailed in Figure 9, with an assumed initial AD process and final steps followed by bulk liquid long-term storage and fertilizer/solids handling. Important additional assumptions detailed in the sidebar ***Assumptions for Cost and Performance Indicators***.

As systems aim to achieve greater levels of reductions in N, P, and volume (Figure 11), complexity increases, as do CAPEX and OPEX expenditures (Figure 10). Across the various approaches summarized, CAPEX expenditures range from \$4 to \$77 cow^{-1} year^{-1} while OPEX range from \$12 to \$317 year^{-1}, both demonstrating large spreads in costs, with particularly high costs associated with higher performances. OPEX costs can be of greatest concern, given the higher annual range and continued annual costs for the lifetime of the project, as well as some government grant programs available to producers focused primarily on CAPEX.

The most appropriate technological approaches for a dairy will depend on whether dairies are primarily trying to manage P, N, or volume. For example, dairies with P management concerns and limited worries related to N and volume may be able to achieve their goals at a relatively low total cost using a first-tier approach to recovery of fibrous and fine solids. For those dairies in need of significant N partitioning or removal, more complex systems will be required.

Though technologies targeting ammonia-N are much more expensive than those targeting P, avoided manure management costs are an important factor that may offset those higher costs under some circumstances. Figure 12 shows the impact of incorporating systems with high N removal on net costs when hauling costs are high due to limited available land, restrictive N management regulations, or a large volume of manure produced (such as highly dilute flush systems). In this figure, avoided costs were calculated assuming 25%, 35%, 50%, and 75% manure hauling in the baseline scenario (no NR), using similar assumptions to those discussed for Table 1.

Lastly, though reduction in volume is generally not the first motivation for adoption of NR technologies, there may be some important benefits in the form of reduced cost of cleaning, maintaining, or adding required long-term storage capacity — benefits not captured in this analysis. Though costly, clean water approaches could provide substantial volume reduction while maintaining the bulk of nutrients for use on fields.

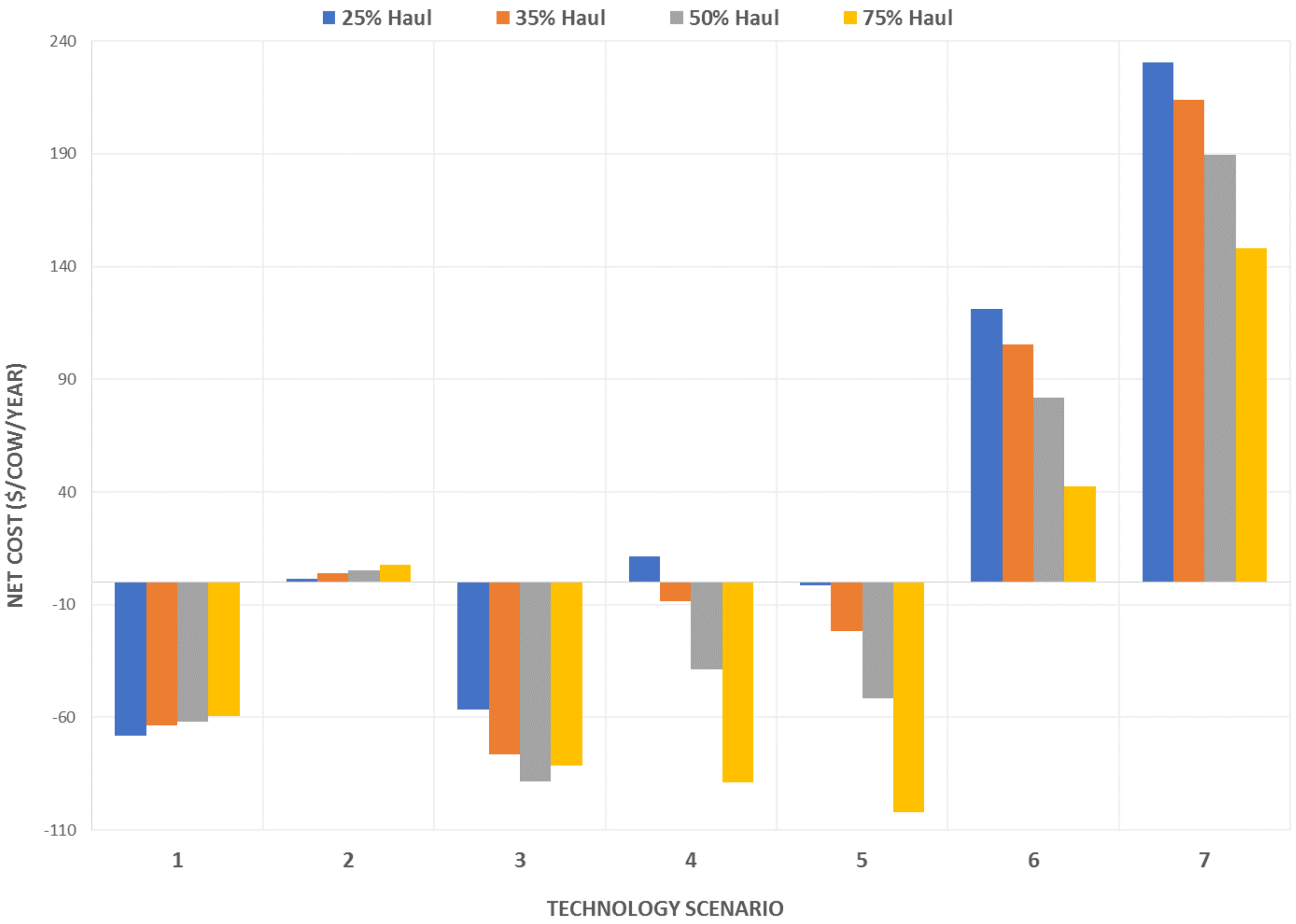

Figure 12. Net costs (CAPEX + OPEX minus avoided manure management costs minus revenues from sales of products) for each technology scenario, with varying assumptions about the percentage of manure needing long distance hauling prior to technology adoption. Technological scenarios are detailed in Figure 9, with an assumed initial AD process and final steps followed by bulk liquid long-term storage and fertilizer/solids handling. Important additional assumptions detailed in the sidebars ***Assumptions for Cost and Performance Indicators and Baseline Manure Management Scenario for Calculating Avoided Manure Management Costs*** (with percentage of manure hauled varied as described in this figure). These results compare the relative net costs of various approaches and should not be viewed as an indication that net revenues and avoided costs exceed CAPEX and OPEX, because of important site-specific costs not included in these calculations.

Conclusion

NR is a relatively new and still evolving area of technology within the dairy industry. While primary solids separation has been implemented on many dairies in the US, technologies for partial advanced nutrient separation and clean water were being used at only a few dozen of the largest dairies across the US as of mid-2017 (Newtrient 2017).

Recognizing that nascent technological sectors often experience rapid gains, especially when coupled with intensifying regulatory concerns related to air quality, water quality, and climate, it is very likely that new technologies appropriate for dairies will continue to emerge. For technological approaches that are already being used, substantial refinements are likely — not the least of which is ongoing development of means to convert recovered nutrients and other co-products to preferred forms. Conversion to preferred forms that are easier to transport, store, and spread with existing farm equipment would greatly enhance the potential for revenues to offset some costs. And finally, as commercial application of specific technological approaches proceeds, there will likely be improved third-party data and performance cost reports, providing more, and in some cases better, information to support decision-making. Lastly, policy incentives such as nutrient trading markets may also be important to spurring adoption.

While not a magic bullet, NR technologies, used in combination with enhanced manure and fertilizer application management, have the potential to improve overall manure management — and to provide new options to dairies that are seeking to produce milk both sustainably and profitably.

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