Development and Application of the Newtrient Evaluation and Assessment Tool (NEAT): A Methodology for Comparing Dairy Manure Treatment Technologies

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Abstract

The U.S. dairy industry is voluntarily playing a critical role in improving dairy sustainability. In 2016, Newtrient, on behalf of the U.S. dairy industry, formed a Tool Assessment Team (TAT) comprised of dairy manure management academic and industry professionals. The TAT conducted a verification and catalog of available dairy manure treatment technologies (MMT); results are in Newtrient's online Technology Catalog. Catalog development revealed the need to establish a set of environmental and farm operational-based Critical Indicators (CIs) that collectively quantify a MTT's environmental and social impact on farm sustainability. The International Organization for Standardization development process was used as the basis to develop a novel evaluation methodology, called the *Newtrient Evaluation and Assessment Tool* (NEAT), for evaluating MMT types. Six specific CIs were selected based on key environmental based challenges/opportunities facing the dairy industry. The CIs were nitrogen recovery, phosphorus recovery, liquid manure storage requirements, greenhouse gas reduction, odor reduction, and pathogen reduction. A literature search was performed to evaluate 20 manure treatment technology types. A scoring system relative to the baseline condition of long-term anaerobic manure storage, was developed and applied to each technology and an appropriate relative score for each critical indicator was determined. The NEAT results are presented in an easy to understand dashboard called the *NEAT Matrix*. Results confirm that there is no single technology type that can address the six CIs but a combination of two or more strategically aligned solutions are possible.

Keywords: Sustainability, Manure management, Nutrients, Emissions, Manure storage, Pathogens

1. Introduction

The North America dairy industry is faced with unprecedented sustainability challenges – economic, environmental and social – in part due to the perceived or actual impacts dairy farms can have on the local, regional and global environment. Most of the challenges stem from the storage and land application of manure. Long-term storage of manure is a water quality best management practice (BMP) where stored manure is recycled for crop production. However, long-term (anaerobic) manure storage produces gaseous emissions that include methane, a greenhouse gas (GHG), ammonia-N, a precursor to formation of atmospheric fine particulate matter, and various odorous emissions that can be offensive to farm neighbors. Runoff and infiltration from fields that received manure organic matter and nutrients can occur, with undesirable impacts on soils, water quality, air quality, and ecosystem imbalance. Impacts vary from none to substantial from farm to farm but overall, society's perception of dairy farm operations and the industry as a whole is affected.

The U.S. dairy industry is voluntarily playing a critical role in working "towards sustainability" (Scott & Gooch, 2017). As a result of the consolidation of the dairy industry, manure treatment technologies are being developed and marketed that target larger operations. The goal is to help farms work on continuous improvement on sustainability issues while operating at large scale. Unfortunately, the efficacy and economics of the treatment technologies are not always well established. As a result, the relative costs and impacts are often difficult to compare, although its importance is realized. Future work outside the purview of this study is planned for discussion and dissemination of technology costs.

Newtrient, on behalf of the U.S. dairy industry, formed a Technology Assessment Team (TAT) in 2016, comprised of a cross section of academic and industry professionals with in-depth expertise in dairy manure management. One of the first tasks assigned to the TAT was to conduct systematic verification and catalog dairy manure treatment technologies available in the United States. A two-year effort to identify and evaluate available manure treatment technologies resulted in the Newtrient online

Technology Catalog (Catalog) with over 200 entries (Newtrient, 2018). The development of the catalog confirmed the need for a method of comparing manure treatment technologies. Based on this need, comprehensive research was conducted to determine if such a method exists. The research indicated the lack of available performance criteria and comparable information. Acting on this from an opportunity perspective, a project was undertaken that resulted in the development of a novel methodology for scoring types of manure treatment technology for their impact on identified Critical Indicators (CIs). This process is called the *Newtrient Evaluation and Assessment Tool (NEAT).* The NEAT process was developed by adapting the International Organization for Standardization (ISO) development process (ISO, 2018).

International Organization for Standardization, the world's largest developer of voluntary international standards, facilitates world trade by providing common standards between nations. Thousands of standards have been established covering everything from manufactured products and technology to food safety, agriculture, and healthcare. The ISO standards aid in the creation of products and services that are safe, reliable, and of good quality. The standards help businesses increase productivity while minimizing errors and waste. By enabling products from different markets to be directly compared, they facilitate companies entering new markets and assist in the development of global trade on a fair basis. The standards also serve to safeguard consumers and the end-users of products and services, ensuring that certified products conform to the minimum standards set internationally. The ISO uses a simple, yet robust, process to develop standards (ISO, 2018b). This process provides a credible and effective standardized method based on applying seven stages to the standard development process. The stages are: 1) Preliminary, 2) Proposal, 3) Preparatory, 4) Committee, 5) Enquiry, 6) Approval, and 7) Publication. The standard ISO process uses multiple large Working Groups (WG) to produce documentation that is then sent to a Committee for review prior to publication as a standard (Fig.1).

The NEAT process was applied to 20 different types of dairy manure treatment technologies to quantify their impact on the six CIs that are most important to dairy industry continuous improvement on sustainability. These are nitrogen recovery, phosphorus recovery, impact on storage requirements, greenhouse gas reduction, odor reduction, and pathogen reduction. A scoring system, relative to the baseline condition of storing manure in a long-term (anaerobic) manure storage, was developed, applied to each technology type and an appropriate relative score for each CI was determined. The results, presented in an easy to understand dashboard called the *NEAT Matrix,* will be included in the Catalog. The objectives of this paper are to present: 1) the NEAT methodology developed by adapting the ISO standard development process to produce the *NEAT Matrix*; and 2) the results of the application of NEAT to 20 common types of dairy manure treatment technologies.

2. Methodology

2.1. NEAT development

The Newtrient TAT adapted the standard ISO process by using the team to serve as the WG and Committee. A major reason for the experts serving on both the WG and Committee was due to limited resources; no public funds were used for the work and the list of qualified experts in the field of dairy manure treatment technology is very limited.

Figure 1 shows the ISO Standard Development Process vs. Newtrient Process. The adapted methodology (Fig. 1) sought to strike a balance between driving progress through the combined tacit knowledge embedded in the TAT, the specific context arising from on-farm practice, the explicit knowledge informed by formal documentation and publications, and the consensus opinion of the TAT members. The NEAT methodology leveraged the existing knowledge and created new knowledge through the engagement and evaluation process itself. In addition, this allowed progress to be made by not demanding perfection, while transparently recognizing confidence levels, limitations, and potential gaps the TAT would like to see closed in the future. The NEAT methodology embraced the four key principles of ISO standard development:

1. Responding to a need in the market
2. Based on expert opinion
3. Developed through a multi-stakeholder process
4. Based on a consensus

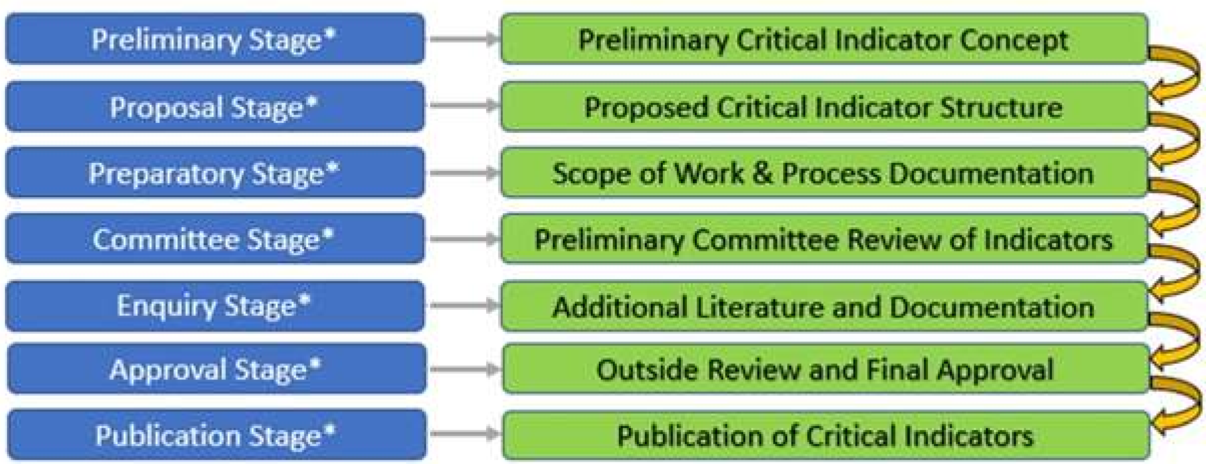

Fig.1- ISO Standard Development Process vs Newtrient Process.

The TAT developed and utilized the following seven steps, adapted from the ISO Standard Development Process, to evaluate the environmental impact each type of dairy manure processing technology had based on six select CIs using long-term (anaerobic) manure storage as a baseline for comparisons. The NEAT process utilized the ISO process, but removed the sharing of the WG in the Preparatory Stage and expanded the sharing of the Working Drafts (WD) to the Enquiry Stage.

2.2. Steps of the modified ISO

2.2.1. Preliminary critical indicator concept

The *Preliminary Stage* consisted of conceptualization and clarification of how the TAT could best respond to Newtrient board members, dairymen, regulators, and vendors requesting that Newtrient take the value of the Catalog to the next level. It was recognized that, by evaluating the impact each type of technology has on critical environmental and operational indicators and grouping the technologies by CI, the dairy industry would have a resource for addressing specific issues that were affecting individual dairy operations. At a high level, this resource will help dairy farmers evaluate manure treatment technologies that will decrease their environmental footprint and increase the opportunity to create more value from manure.

The discussion below provides details about each CI and rationale for inclusion in the initial release of the Newtrient Critical Indicator Matrix. While there were certainly many indicators, the decision was made to investigate the indicators that were of most concern to the industry from an operational and environmental sustainability perspective. For the following highlighted reasons these CIs were identified:

1. Nitrogen recovery – The Federal judge's ruling in CARE v Cow Palace (2015) in Washington State determined that, for this farm, dairy manure stored in lagoons, used as fertilizer on fields and composted, was considered a "solid waste" under the federal Resource Conservation Recovery Act ("RCRA") and posed an "imminent and substantial danger to public health and the environment", because of how the manure was managed. This decision and many other groundwater, nutrient run-off, and air quality issues nationwide makes this a critical area of

concern. Because nitrogen is an essential plant nutrient, technologies have been evaluated relative to their ability to "recover" nitrogen for beneficial use relative to long-term (anaerobic) manure storage.

2. Phosphorus recovery – In areas of the country where there are significant issues with algal blooms and total maximum daily loading (TMDL) limits set by the EPA, one of the key nutrients identified is phosphorus. The regulations around phosphorus and the issues related to its regulation and use makes this a key CI for the dairy industry. Because phosphorus is an essential plant nutrient, technologies have been evaluated relative to their ability to "recover" phosphorus for beneficial use relative to long-term (anaerobic) manure storage.
3. Liquid manure storage requirements – One of the key issues regarding on-farm implementation of any manure management technology relates to the use of the final products and the ability to use the contained nutrients in a proper way, utilizing the 4R Nutrient Stewardship framework (Nutrientstewardship, 2018). Increased data are available showing that the frequency and intensity of rainfall events directly correlates to the runoff of manure-derived nutrients. Greater storage capacity facilitates more flexibility in applying manure to fields at appropriate times and rates, making storage a CI.
4. Greenhouse Gas reduction – Efforts by retailers to quantify the GHG footprint of their supply chain, along with a recent statute-California's SB-1383 (2016) that mandates California reduces its GHG emissions 40% below 2013 levels by the year 2030 – makes this a CI from all aspects of dairy sustainability.
5. Odor reduction – Considerable concern related to odors has been expressed by communities and neighbors of animal agricultural operations. Odor emissions from any animal agricultural facility are very difficult to quantify, but significant progress has been made in quantifying the compounds

that are most offensive and applying standards to the odors around various types of facilities. This is a CI that applies to the acceptance and "social license to operate" for dairy operations around the country.

6. Pathogen reduction – In several areas there have been major issues related to runoff from dairy manure and water contamination. In the Pacific Northwest, valuable environmentally sensitive areas like the shellfish beds are prone to contamination, while in other areas of the country, there are issues with contaminated wells and drinking water supplies. Much like the nitrogen recovery indicator, the groundwater and nutrient runoff issues nationwide make pathogen reduction a critical area of concern.

The decision to approach the NEAT process as both a score and method of documenting the source as existing peer-reviewed literature, third party documentation, or expert opinion was based on the goal of creating a user-friendly dashboard that includes the six CIs, their scores, and the reliability of the sources that were used to determine their scores. After reviewing the resources available and the amount of effort that would be required to review and evaluate the more than 200 technologies in the Catalog, the decision was made to concentrate efforts on types of technology rather than on each individual technology. Technology category is used here to describe each group (more than one technology type) having the same operational concept or generating comparable products. For instance, primary solid-liquid separation is a category of technology types such as screw-press, sloped screen, rotary drum, etc. After considerable discussion, relating to effective consolidation, five technology categories comprising twenty technology types (Table 1) were defined based on the mechanism of operation and the resulting effect on the manure stream.

Table 1- Defined manure treatment technology categories and types evaluated for impact on critical indicators.

Technology Category	Evaluated Technology Types
Primary solid-liquid separation	- Centrifuge - Rotary screen - Screw press - Slope screen
Secondary solid-liquid separation	- Clean water membrane - Evaporative technologies - Ultrafiltration membrane
Physical and biochemical stabilization	- Active solids drying - Composting - Drum composter bedding - Surface aeration
Nutrient recovery	- Ammonia stripping - Chemical flocculation - Struvite crystallization - Nitrification/denitrification
Energy recovery	- Anaerobic digestion - Gasification - Hydrothermal Carbonization - Pyrolysis - Torrefaction

2.2.2. Proposed critical indicator structure

The TAT set out to confirm an evaluation of this sort was needed and drafted a scope of work for the CI evaluation that was modeled on an ISO New Work Item Proposal. Newtrient's leadership needed to determine if there was a need to perform this exercise. At Newtrient's request to the Innovation Center for U.S. Dairy, an initial literature review was conducted by Dr. Rajesh Chintala, Director of Nutrient Management & Stewardship. Dr. Chintala concluded that peer reviewed literature was often not available, easily sourced, or readily interpreted for many of the CIs. This indicated that the requested technology evaluation was indeed necessary and that adding this information to the Catalog would be of benefit to the industry.

Based on this confirmation, and the experience of team members in similar areas, Newtrient made the decision to develop the *NEAT* process and to evaluate technology types based on peer reviewed publications when available, third party documentation when available, and by bringing together experts in the field of manure management to realize a consensus of qualified perspectives when other sources of information were not available. The TAT made specific assignments to small teams with members selected based on their areas of expertise.

2.2.3. Scope of work and process documentation

Having decided on this criterion for evaluating the technology types, Newtrient expanded on the initial literature search to include third party reviewed articles and other published works and used the findings from this broadened search to supplement the information previously collected. For this, Newtrient contracted with Green Insights (www.greeninsights.net/), an environmental research company, for assistance with this effort. Literature review outputs were reviewed by small teams made up of the TAT as well as development of a score recommendation for each CI. This constituted the *Preparatory Stage* of the process.

2.2.4. Preliminary committee review of indicators

Following the Green Insights literature review and small team efforts, the TAT was assembled to review the findings and scoring recommendations presented by the small teams and reach a consensus opinion on the NEAT scores for each technology type. TAT members commented and voted on the draft NEAT scores using a general scale of low, medium and high and whether the effect was positive or negative. When necessary, drafts were tabled until consensus by greater than a two-thirds vote was reached on the technical content.

In addition, the TAT discussed and determined the next steps of the project, which included:

1. Discussed if the report would be available for public comments before it was finalized. Pros include increases the alignment of our process with ISO; ability to enhance the content; makes the final product more robust; and increases process transparency. Cons include adds time to the process and requires additional resources to track and manage the review of the comments.
2. Discussed proper explanation of how dryers, torrefaction, gasification, and pyrolysis impact nitrogen recovery, phosphorus recovery, storage reduction, and GHG reduction related to regulatory, output and value proposition.
3. Decided that differentiating criteria scoring based on flush, scrape, and dry lot collection systems was not realistic given the research available, although we realize that collection system affects manure characterization, flow rate, costs, and potentially performance and downstream impacts.
4. Decided that each technology type would be scored based on the references related to the effect of the individual component and not a larger combined system.
5. Decided that due to the extreme variability within technology types, Capital Expenditures (CapEx) and Operating Expenditures (OpEx) would not be included in the scoring, because it does not yield meaningful guidelines for dairy farmers.
6. Agreed on the following assumptions:
    a. The process and scoring would be focused on the output of the specific type of technology and not the entire system in the several cases where the technology cannot operate in a

stand-alone fashion. Only immediate impacts were considered. This study does not attempt life cycle assessment.

   b. Post-process materials would be handled in a way that does not impact or affect the NEAT scoring.
   c. Dryers, torrefaction, gasification, and pyrolysis would have appropriate emission control components and the purpose of these technologies is to dry wet solids.

7. Decided to group flocculation/polymer and coagulation technologies as a single technology type and those technology types that require these additives for operation were rated based on their inclusion.
8. Decided that for those technology types that require coarse solids separation, (e.g., rotary drum or screw press), before a composter/bedding recovery technology, we will include a comment regarding the inclusion of coarse solids separation on the front side and odor-reduced aspect of the end-product, while acknowledging the unintended consequence of odor from the process.
9. Decided to include a summary of required air control devices to address odors for evaporative and drying technology types.
10. Evaluations assumed that technologies and processes will be designed, implemented, and operated correctly.
11. Decided that appropriate comments to the unique characteristics of membrane technology type and explanations regarding impact on storage, pathogens, and nitrogen and phosphorus recovery would be included in the technology summary.
12. Decided to reach out to individual experts to gather their insights and recommendations related to our findings. The committee would make final decisions regarding all scores and the final content of the published results.

13. The final draft report should be reviewed by a team of outside experts prior to incorporation into the Catalog and public comment may be solicited for a designated period after publication and before the document is finalized.

The TAT reviewed the recommendations of the small groups to confirm the comments and scores for each CI. If peer reviewed literature was cited, the recommendation was based on that literature unless there were conflicting sources. If there was no peer reviewed literature, but there was third party validated data, the recommendation was based on the third-party documentation. In all other cases, the CI score was assigned based on the consensus opinion of the TAT.

Once the TAT completed assigning scores to all the technology types for each CI, the process of reviewing, improving, and writing the final documentation was undertaken and described as below. The goal of this effort and the rest of the *Enquiry Stage* of the process was to complete documentation of the entire process as well as to finalize the NEAT dashboard (Fig. 2).

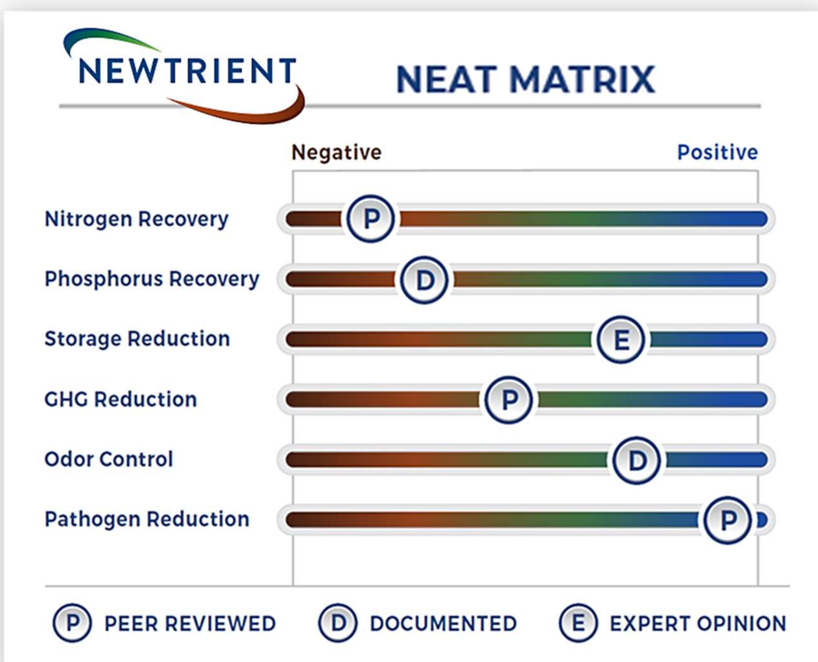

Fig. 1- Generic example of the NEAT Matrix.

2.2.5. Additional literature and documentation

The documents were then composed, and the scoring rationale was refined in a series of NEAT reports. These reports were assigned to a small team of members for review, discussion, and dialogue. The process included:

a) Draft critical indicator report stage

A draft NEAT report of each technology type was written. It included a dashboard, a table of results, an overall summary of the technology, the reason for the NEAT score, and selected references.

b) Critical indicator report review stage

The draft NEAT report of each technology type was then assigned to a small group for editing, additions, and review.

c) Draft document stage

All the final NEAT documents were then compiled and added to a full technical document that detailed the process and methodology of this study in the final draft NEAT report.

d) Document review stage

The final draft NEAT report was shared with the TAT for final review.

2.2.6. Outside review and final approval

The final draft NEAT report, approved by the TAT, was then shared with a select group of independent reviewers for a final review, discussion, and dialogue regarding edits. The *Approval Stage* of the process included all technical, formatting, and grammatical changes to the final draft NEAT report.

The TAT was the final authority to determine the accepted refinements. All refinements required a 2/3 majority vote of the TAT with no sustained objections.

2.2.7. Publication of critical indicators

The TAT then submitted the final NEAT report to the Newtrient CEO for approval to incorporate the *results* into the Catalog. The Publication Stage was initiated by the TAT releasing the final document for incorporation into the Catalog.

3. Results

The NEAT matrix developed for each technology type is shown in the supplementary material. For most of the studied technology types, all values were calculated as a percentage, positive, negative or neutral, relative to a baseline condition of manure stored in a long-term (anaerobic) manure storage. For the types of technology that treat the solid fraction, the baseline was the direct use of separated solids as a soil amendment. A summary of the results of the literature search and technical assessments is provided in Table 2. Table 2 also shows key references that could be used in developing the indicator matrix. These references provide more details about the operational concepts and the application of each technology type.

Table 2- Summary of the application NEAT to 20 dairy manure types of treatment technology for six critical indicators. Values shown with a "+" indicates a positive change for the indicator while those with a "-" indicates a negative (reduced) change.

Technology Type	**Nitrogen recovery (%)**	**Phosphorus recovery (%)**	**Storage reduction (%)**	**GHG reduction (%)**	**Odor control (%)**	**Pathogen reduction (%)**	**Key References**
Active Solids Drying	Low +	Neutral	High +	Medium +	High +	High +	Roos (2008); Fushimi et al. (2010); Schoumans, Rulkens, Oenema, & Ehlert (2010); Rehl & Müller (2011); Fuchs & Drosg (2013); Delele, Weigler & Mellmann (2015); Drosg, Fuchs, Al Seadi, Madsen & Linke (2015); Hamilton et al. (2016); Yang, Hao, & Jahng (2017).
Ammonia Stripping	Medium +	Neutral	Neutral	Neutral	Medium +	High +	Bonmatı & Flotats (2003); Alitalo, Kyrö, & Aura (2012); Jiang et al. (2014); Drosg et al. (2015); Wallace, Budaj & Safferman (2015); Zhao et al. (2015); Ukwuani & Tao (2016); Vaneeckhaute et al. (2017); He et al. (2018); Frear, Ma & Yorgey (2018).

Anaerobic Digestion	Low -	Neutral	Neutral	High +	High +	High +	Welsh, Schulte, Kroeker, & Lapp (1977); Pain, Misselbrook, Clarkson & Rees (1990); Wright, Inglis, Stehman, & Bonhotal (2003); Topper, Graves & Richard (2006); Gooch, Pronto & Labatut (2011); Massé, Talbot & Gilbert (2011); Möller & Müller (2012); Summers & Williams (2013); Page et al. (2014); Owen & Silver (2015); Holly, Larson, Powell, Ruark & Aguirre-Villegas (2017).
Centrifuge	Low +	Medium +	Low +	Medium +	Low +	Neutral	Møller, Hansen & Sørensen (2007); Hjorth, Christensen, Christensenn & Sommer (2010); Neerackal et al. (2015); Hamilton et al. (2016); Holly et al. (2017); Liu, Carroll, Long, Roa-Espinosa & Runge (2017); Frear et al. (2018).
Chemical Flocculation	Medium +	High +	Low +	High +	Medium +	Neutral	Fangueiro, Senbayran, Trindade & Chadwick (2008); Garcia, Szogi, Vanotti, Chastain & Millner (2009); Hjorth et al. (2010); Neerackal et al.

							(2015); Liu, Carroll, Long, Gunasekaran & Runge (2016); Bronstad, Frear, Yorgey & Benedict (2017); Holly et al. (2017); Frear et al. (2018).
Clean Water Membrane	High +	High +	Medium +	Low +	Neutral	Neutral	Wong et al. (2009); Chiumenti, da Borso, Chiumenti, Teri & Segantin (2013a); Pauls (2014); Drosg et al. (2015); Budaj (2016); Bolzonella, Fatone, Gottardo & Frison (2018); Frear et al. (2018).
Composting	Low -	Neutral	Low +	Low +	Low +	High +	Bradley, A. J., Leach, K. A., Archer, S. C., Breen, J. E., Green, M. J., Ohnstad, I., & Tuer, S. (2014); Harrison, E., J. Bonhotal, & M. Schwarz. (2008); Larney, F. J., Sullivan, D. M., Buckley, K. E., & Eghball, B. (2006); Michel Jr, F. C., Pecchia, J. A., Rigot, J., & Keener, H. M. (2004); Misselbrook, T. H., & Powell, J. M. (2005); Spencer, R. (2016); SUSCON (2017).

Drum Composter Bedding	Low -	Neutral	Low +	Low +	Low +	High +	Michel, Pecchia, Rigot & Keener (2004); Larney, Sullivan, Buckley & Eghball (2006); Harrison, Bonhotal & Schwarz (2008); Bradley et al. (2014); Spencer (2016).
Evaporative Technologies	High +	High +	Medium +	Medium +	High +	High +	Hjorth et al. (2010); Flotats et al. (2011); Chiumenti et al. (2013a); Fuchs & Drosg (2013); Guercini, Castelli & Rumor (2014); Drosg et al. (2015); Vondra, Máša, & Bobák (2016); Vondra, Masa & Bobak (2018).
Gasification	High -	High +	High +	High +	High +	High +	Priyadarsan, Annamalai, Sweeten, Mukhtar & Holtzapple (2004); Cantrell, Ro, Mahajan, Anjom & Hunt, (2007); Ro, Cantrell, Elliott & Hunt (2007); Hamilton et al. (2016); Hou, Velthof, Lesschen, Staritsky& Oenema (2016); Pelaez-Samaniego et al. (2017).
Hydrothermal Carbonization	Medium -	High +	Medium +	High +	Medium +	High +	Heilmann et al. (2014); Acharya, Dutta & Minaret (2015); De Mena Pardo, Doyle, Renz & Salimbeni

							(2016); Toufiq Reza et al. (2016); Bakri, Iwabuchi, Ito & Taniguro (2017); Dia et al. (2017); Wu et al. (2017); Wu, Zhang & Yuan (2018).
Nitrification Denitrification	High -	Medium +	Neutral	High +	High +	Medium +	Willers, Derikx, Ten Have, & Vijn (1996); Bèline & Martinez, (2002); Obaja, Mace, Costa, Sans, & Mata-Alvarez (2003); Vanotti, Millner, Hunt & Ellison (2005);Vanotti, Szogi, Millner, & Loughrin (2009); Li et al. (2012); Riaño & García-González (2014); García-González et al. (2016); Xu, Adair, & Deshusses (2016); Yang, Deng, Zheng, Wang, & Liu (2016); Lia, Zhao, Pan & Mitloehner (2018).
Pyrolysis	High -	High +	High +	High +	High +	High +	Massie (1972); Shinogi & Kanri (2003); Cantrell et al. (2007); Lehmann & Joseph (2009); Cantrell, Hunt, Uchimiya, Novak & Ro (2012); Kumar & Nanda (2016); Hamilton et al. (2016); Hou et al. (2016); Pelaez-Samaniego et al. (2017).

Rotary Screen	Low +	Low +	Low +	Low +	Low +	Neutral	Forbes, Easson, Woods & McKervey (2005); Fangueiro et al. (2008); Hjorth et al. (2010); Neerackal et al. (2015); Hamilton et al. (2016); Holly et al. (2017); Ma, Neibergs, Harrison & Whitefield (2017)
Screw Press	Low +	Low +	Low +	Medium +	Low +	Neutral	Møller, Lund & Sommer (2000); Møller, Sommer & Ahring (2002); Forbes et al. (2005); Fangueiro et al. (2008); Hjorth et al. (2010); Neerackal et al. (2015); Hamilton et al. (2016); Holly et al. (2017).
Slope Screen	Low +	Low +	Low +	Medium +	Low +	Neutral	Zhang & Westerman (1997); Chastain, Vanotti, & Wingfield (2001). Hjorth et al. (2010); Frear, Wang, Li & Chen (2011); Cocolo (2014); Neerackal et al. (2015); Hamilton et al. (2016); Frear & Yorgey (2017); Zhang (2017).

Struvite Crystallization	Low +	High +	Neutral	Neutral	Neutral	Low +	Zhang, Bowers, Harrison, & Chen (2010); Rico, García & Rico (2011); Shen, Ogejo & Bowers (2011); Hilt et al. (2016); Tao, Fattah & Huchzermeier (2016); Frear et al. (2018).
Surface Aeration	Low +	Neutral	Neutral	Medium +	High +	Neutral	Amon, B., Kryvoruchko, V., Amon, T., & Zechmeister-Boltenstern, S. (2006); Martinez, J., Guiziou, F., Peu, P., & Gueutier, V. (2003); Ndegwa, P. M., Wang, L., & Vaddella, V. K. (2007); Ndegwa, P. M. (2003); Westerman, P. W., & Zhang, R. H. (1997); Zhang, Z., & Zhu, J. (2005); Zhang, Z., Zhu, J., & Park, K. J. (2006)
Torrefaction	Medium +	High +	Medium +	High +	High +	High +	Heilmann et al. (2014); Acharya, Dutta & Minaret (2015); De Mena Pardo, Doyle, Renz & Salimbeni (2016); Toufiq Reza et al. (2016); Bakri, Iwabuchi, Ito & Taniguro (2017); Dia et al. (2017); Wu et al. (2017); Wu, Zhang & Yuan (2018).

Ultrafiltration Membrane	Medium +	High +	Medium +	High +	Low +	High +	Wong et al. (2009); Bolzonella et al. (2018); Chiumenti, da Borso, Teri, Chiumenti & Piaia (2013b); Wallace et al. (2015); Safferman et al. (2017); Frear et al. (2018).

4. Discussion

The goal of this research was to develop a novel method to score types of manure treatment technology for their impact on environmental sustainability and share the outcomes with dairy farmers and their key advisors via the Newtrient Catalog. This will enable dairy farmers and stakeholders to make better informed decisions regarding their investments and improve their ability to make progress in addressing the critical areas that are identified.

The study and documentation have been valuable in setting the groundwork for providing information to the dairy industry and animal agriculture at large. One of the lessons learned is the incredible lack of information available for evaluating technology efficacy particularly in peer reviewed journals. Clearly, to identify the technologies that exist or are developed to solve the problem of negative environmental impact of animal agriculture, industry in consultation/involvement with academia will need to find ways to fund and encourage this type of research. It is the hope of the authors that the detailed results of this work can become a resource for researchers to identify areas that need study. Targeting these topics for undergraduate and post-graduate projects will prepare students for degree worthy efforts while contributing valuable information to the industry.

This work confirmed the previously held opinion that there is no single type of technology available that will meet all the needs identified by these CIs. Often the specific issue to be addressed requires multiple "steps" to achieve the desired outputs. This requires a systems-based approach that integrates many technologies. One of the biggest challenges faced by farmers is finding financial and technical resources to bring all these pieces together. This is particularly true because many times the introduction of a new technology results in unexpected consequences for an operation. Trade-offs must then be made that can affect the economics of a project and impact operations in ways that may not be apparent. The development and study of integrated manure management systems is an area in need of additional research.

One aspect that made this study challenging was the diverse regional manure management practices that at first seem inconsequential but can have a significant impact on what technologies can be used and, in some cases, if a technology is required at all. In the arid areas of the southwest the need for driers, except for a few weeks of the year, is non-existent. In these areas, solar drying in thin layers could prevent the formation of GHGs and reduce transportation costs considerably. At the same time, in the Pacific Northwest where some areas receive over seven feet of rainfall per year, dewatering and drying any material requires it to be transported, increasing the release of GHG emissions and the cost of transportation. An additional and very important variable relates to the diversity of manure management approaches utilized on U.S. dairy farms. Dairy farms implement a variety of approaches that produce a range of manure outputs, from extremely dilute liquids to dry solids, each at times containing both organic and inert bedding. As such, the form of the manure has important performance and economic impacts to the technologies being reviewed, requiring future Newtrient work to differentiate the matrix by manure management type and its manure output form.

The most significant issues related to the implementation of manure management technologies are the economics. Frequently, the cost of producing a product from manure is significantly higher than the cost of producing a comparable product from an alternative source. The logistics of nutrient management and nutrient recycling in modern agriculture are significantly more difficult than using commercial fertilizer because the use of the nutrients in the form of cattle feed and the production of the feed can be separated by considerable distances. In an ideal situation, forage and concentration production for the dairy would be co-located near or on the farm to minimize hauling and maximize the use of recycled nutrients in systems that mimic the cycles found in nature. But in many circumstances other factors prevent this from happening leading to a difficult conflict between the need for the nutrients and the proper utilization of those remaining after initial use.

Product development is also an area that presents challenges because all too often the products produced from manure are competing with commodity products that are supported by industries that have had ample time and resources to drive down their costs of production and to leverage their market positions in ways that discourages competition on a smaller scale or regional basis. Furthermore, standardization of the characteristics of the products developed from manure is another research area that needs significant attention of researchers and stakeholders. Such standardization will help in reducing the costs of storage and handling of manure products.

A final area that impacts technology development and deployment is the regulatory environment. Conflicting regulatory goals can send mixed signals to vendors and operators and can often result in a "wait and see" attitude that allow problems to exist far longer than they would in the case of a clear regulatory direction. Hopefully this document will serve as a resource for the regulatory community to understand the complexity and technological expertise required to implement successful projects to address operational and environmental problems.

5. Conclusion

This study has produced a new resource for industry, regulators, academia, and anyone interested in reducing the environmental impact of animal agriculture in North America and other countries. The collection of the technologies in the Catalog as well as the evaluation of the CIs using the NEAT process creates a “one-stop shop” for identifying potential solutions to specific environmental and operational problems and opportunities for capturing value from manure. Applying the NEAT matrix clearly indicates there is no single type of technology available that meets all the environmental and social needs identified by these indicators. The collaborative efforts of academia and industry in communicating new research and providing updated information will be an on-going effort of the authors. Regular reviews of the materials and referenced works will be scheduled as part of the Newtrient Technology Catalog’s ongoing maintenance. Future research should be conducted on evaluating the selected technology types based on their costs and life cycle assessment.

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Declarations of interest

Craig Frear is a principle of BEST, LLC. Dr. Frear is a Board member of the American Biogas Association.

Curt Gooch declares that he has no conflict of interest.

Mark Stoermann holds a patent within this technology sector which is held in ownership within an LLC for which he is a member. Mr. Stoermann is a Board member of the American Biogas Association.

Garth Boyd declares that he has no conflict of interest.

Jerry Bingold declares that he has no conflict of interest.

Rajesh Chintala declares that he doesn’t have conflict of interest.

Dana Kirk is a paid technical advisor for GGP America and Newtrient and has ownership in Silvernail Consulting, Inc. and SKS Development, LLC.

Elijah Smith declares that he has no conflict of interest.

James Wallace declares that he has no conflict of interest.

Matt Sutton-Vermeulen declares that he has no conflict of interest.

Hamed El Mashad declares that he has no conflict of interest.

Frank Mitloehner declares that he has no conflict of interest.

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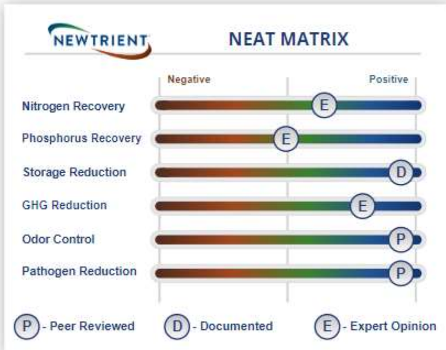
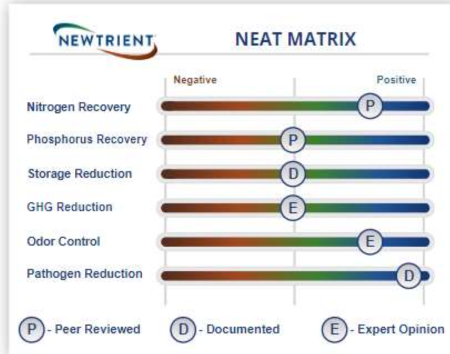
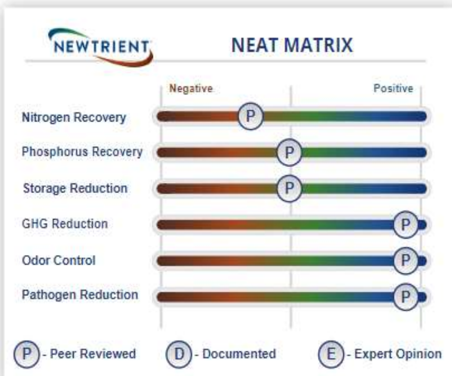
Supplementary material

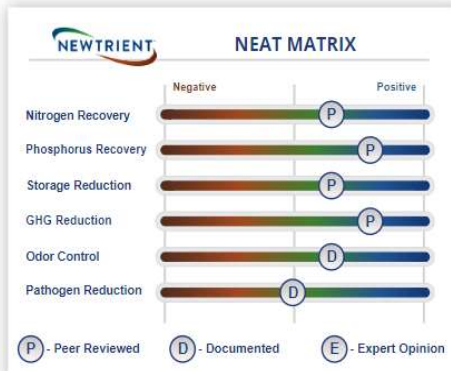




Active solids drying

Ammonia stripping



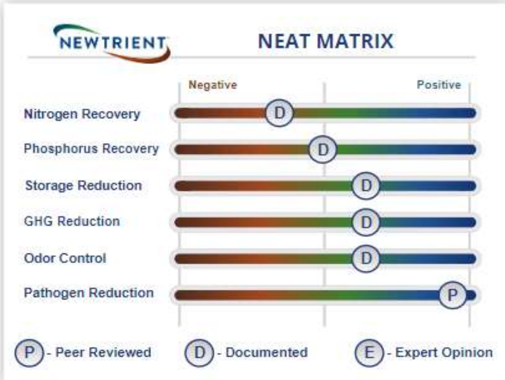


Anaerobic digestion

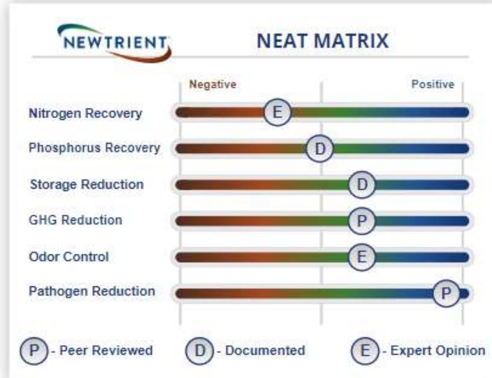
Centrifuge

Chemical flocculation

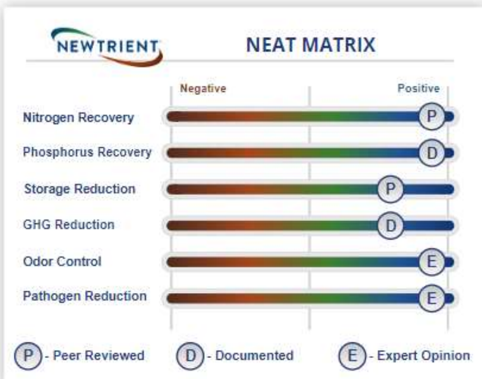
Clean water membrane systems



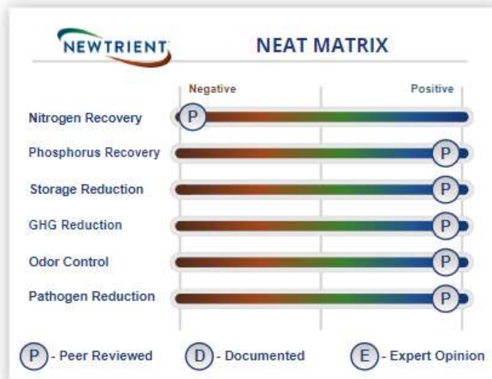
Composting



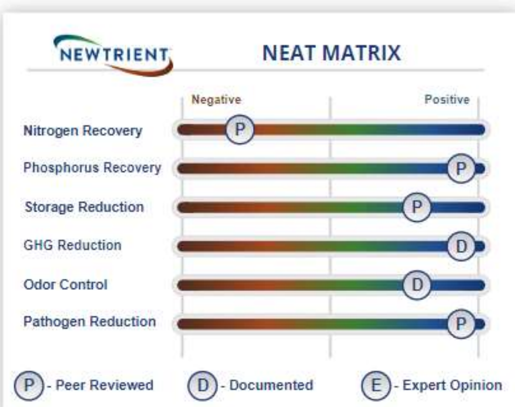
Drum composter / Bedding recovery



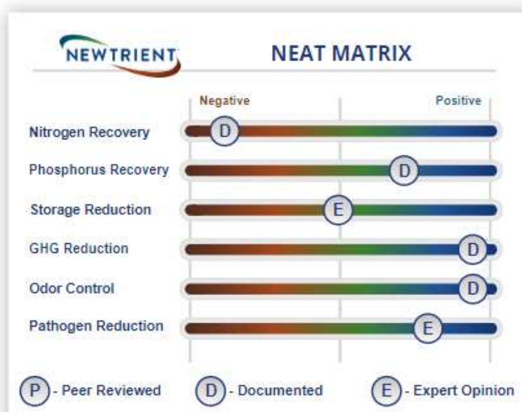
Gasification



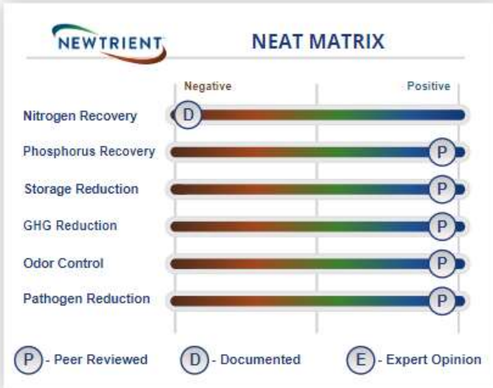
Evaporative technologies

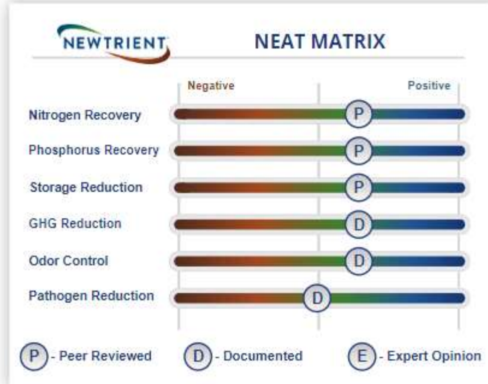


Hydrothermal carbonization



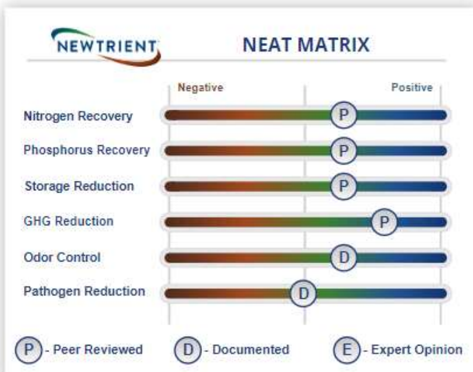
Nitrification/Denitrification

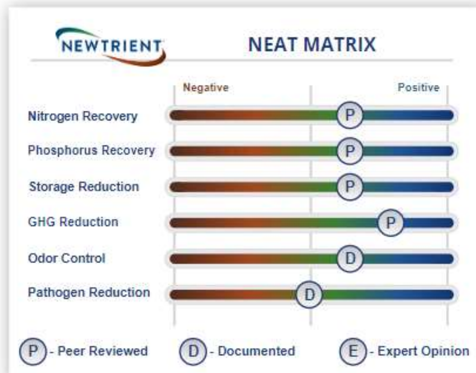




Pyrolysis

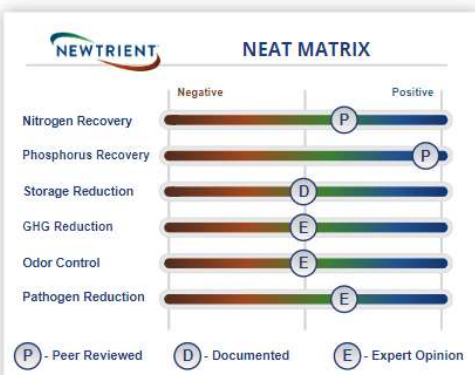
Rotary screen separator

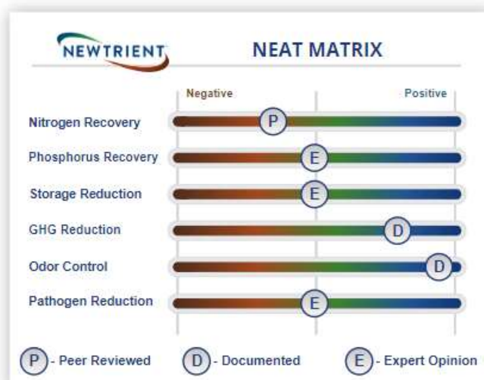




Screw press separator

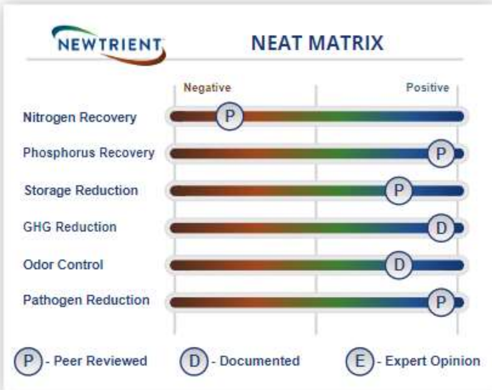
Slope Screen separator

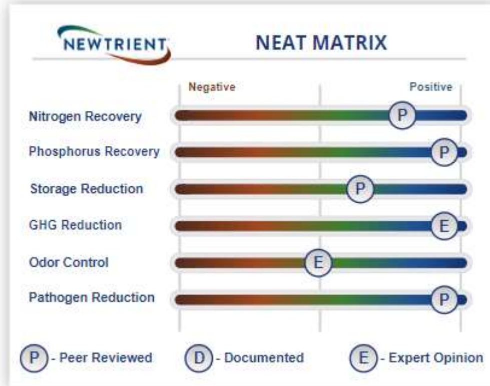




Struvite Crystallization

Surface Aeration





Torrefaction

Ultrafiltration membrane