H2Ohio Technology Assessment Program (TAP)

Final Report

Assessment of Agricultural Nutrient Management Technology Submission

The Andersons Struvite DG® Enhanced Efficiency Fertilizer

January 2022

TETRA TECH

EXECUTIVE SUMMARY

The Andersons of Maumee, Ohio has submitted a technology proposal for their Struvite Dispersible Granule (DG) Fertilizer to the Ohio Environmental Protection Agency' (Ohio EPA's) H2Ohio Technology Assessment Program (TAP) for the purpose of addressing the Lake Erie algal blooms and associated nutrient loading. The TAP objectives addressed by Struvite DG® are reduction of nutrient loading to rivers, streams, and lakes, reduction of toxic algal blooms, and improvement of nutrient removal in wastewater treatment systems through phosphorus recovery. Published reports have claimed that recovery of phosphorus from struvite can (1) reduce effluent runoff from wastewater and the potential for pipe blockage following anaerobic digestion of biosolids in wastewater treatment plants; (2) reduce phosphorus loading when compared to biosolids land applications on already phosphorus-rich fields; and (3) reduce the potential for phosphorus leaching to surface water. Struvite material is most economically formed in an aqueous solution containing at least 50 parts per million (ppm) of soluble phosphate. When the pH of this solution is balanced, and both magnesium and ammonia are either present or added, the relatively insoluble crystals of struvite form. This process allows for the efficient recycling and removal of soluble phosphorus from potentially harmful discharge, such as effluent wastewater.

The Andersons Struvite DG® is a proprietary granular material that upon contact with water, each DG granule disperses into micro particles that move through the crop plant canopy into the root zone. This level of dispersibility delivers nutrients to the plant and can reduce leachate runoff and nutrient loss. The efficacy and environmental fate and transport of the Struvite DG® material has been evaluated in various small-scale studies that are referenced throughout this report. Struvite DG® is currently used in specialty crops like turfgrass, home lawns, and commercial agriculture. The supply of available struvite is currently too low to have a meaningful impact on row-crop agriculture, which has been identified as a potential fatal flaw unless other suppliers can be identified to support the Lake Erie watershed. The Andersons can currently process over 200,000 tons of struvite (e.g., minimum of 60,000 tons estimated to be required for Lake Erie watershed application) for their Struvite DG® material annually at their two processing facilities in Ohio along with other business partnerships that operate struvite recovery and processing facilities in the United States. These facilities are also testing recovery of struvite at livestock farms, food processors, and ethanol facilities. The Andersons currently have the capacity to meet the processing needs of the Lake Erie watershed with the only limitation being the availability of struvite. Recovery of struvite from wastewater sources is currently about 10,000 tons per year for the Andersons.

This report evaluates Struvite DG® against a suite of criteria identified by the TAP using information provided by the Andersons and through a literature review of similar technologies. The small-scale studies and literature evaluated as part of this technology assessment has shown that (1) nutrient recovery is more sustainable when compared to traditional acidulated rock phosphate fertilizers (especially in conserving this non-renewable resource); (2) it can provide a continuous source of phosphorus for plant uptake especially during the later stages of plant development without detriment to crop yield; (3) and leachate runoff can be reduced due to its lower solubility and retention in soil compared to traditional acidulated rock phosphate fertilizers (traditional phosphate fertilizers are derived from phosphate rock that are reacted with sulfuric acid to make them soluble). The biggest limiting factor for this technology is the struvite supply chain currently available for production.

However, the Andersons have identified other reclaimed sources of struvite through their current suppliers that have plans for expanding operations and potential new suppliers. Based on the information provided, Tetra Tech determined that Struvite DG® is very likely to be effective at reducing nutrient loading to Lake Erie but additional evidence needs to be provided to demonstrate it can be used on a large scale. Simulating the effects of management practices through modeling scenarios may also assist in demonstrating the outcome to farmers/landowners on optimizing crop yield and reducing nutrient runoff prior to full-scale application of Struvite DG®.

Tetra Tech did not identify any negative impacts associated with community perception or waste management. Past studies completed for the Andersons Struvite DG® show lower risks to the environment when compared to more soluble acidulated rock phosphate fertilizers. The total estimated costs for recovery, processing, and distribution over the past five years has ranged from $800-$1,200 per ton. Struvite from existing recovery facilities is currently too high priced for agriculture production. However, Tetra Tech identified other economic cost factors that should also be considered including projected revenue generation from the fertilizer, reduction of equipment fouling from precipitation of struvite, reduction of best management practices (BMPs) required, meeting regulatory discharge limits, and energy cost savings. Landowner willingness is a potential barrier due to cost, which could be addressed through financial support provided by the H2Ohio Initiative. A demonstration project targeting widespread adoption of Struvite DG® within the Lake Erie watershed could evaluate the ability of financial incentives to spur farmers/landowners to use this technology and also provide more detailed data about nutrient load and BMP reduction, crop yield, and potential constraints to using the technology within the Lake Erie watershed.

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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
BMP	Best management practice
DAP	Diammonium phosphate
DG	Dispersible Granule
EBITDA	Earnings before interest, taxes, depreciation, and amortization
EPA	U.S. Environmental Protection Agency
HABs	Harmful Algal Blooms
HAWQS	Hydrologic and Water Quality System
lb.	pound
lbs.	pounds
MAP	Monoammonium phosphate
mg/L	Milligrams per liter
Ohio EPA	Ohio Environmental Protection Agency
ORD	Office of Research and Development
Ostara	Ostara Nutrient Recovery Technologies, Inc.
PPE	Personal Protective Equipment
ppm	Parts per million
QAPP	Quality Assurance Project Plan
RFT	Request for Technology
SWAT	Soil and Water Assessment Tool
TAP	Technology Assessment Program
Tetra Tech	Tetra Tech, Inc.
TSCA	Toxic Substances Control Act
U.S. EPA	United States Environmental Protection Agency
USDA	U.S. Department of Agriculture

1.0 INTRODUCTION AND BACKGROUND

H2Ohio (http://h2.ohio.gov) is Ohio Governor Mike DeWine's comprehensive, data-driven water quality plan to reduce Harmful Algal Blooms (HABs), improve wastewater infrastructure, and prevent lead contamination. Governor DeWine's H2Ohio plan is an investment in targeted solutions such as:

- Reducing phosphorus runoff through increased implementation of agricultural best management practices and the restoration of wetlands;
- Improving wastewater infrastructure;
- Replacing failing home septic systems; and
- Preventing lead contamination in high-risk daycare centers and schools.

HABs have been a concern in Lake Erie for decades, and the State of Ohio has a long history of developing solutions to address them. In support of these efforts, state agencies are often presented with new approaches for addressing HABs. These approaches often involve technologies and products that are typically innovative, can be proprietary, and span multiple scientific disciplines. To evaluate these proposals for their efficacy and feasibility, the Ohio Environmental Protection Agency (Ohio EPA) worked with the Lake Erie Commission to create a public advisory council—the Technical Assistance Program (TAP) Team. The H2Ohio TAP Team is comprised of representatives from the private sector, public sector, trade associations, and non-profit companies. The H2Ohio TAP team is conducting an evaluation of technologies designed to treat, control, and reduce HABs in the Lake Erie watershed. H2Ohio initiated the TAP to solicit and evaluate technologies that support one or more of the following five goals:

1. Reduction of nutrient loading to rivers, streams, and lakes;
2. Removal of nutrients from rivers, streams, and lakes;
3. Reduction of the intensity or toxicity of algal blooms;
4. Recovery of nutrients from animal waste; and
5. Improvement of nutrient removal in wastewater treatment systems.

The H2Ohio TAP Team worked to solicit and prioritize technology proposals for further review. A Request for Technologies (RFT) was developed and issued by the Ohio EPA in November 2020 (H2Ohio TAP, 2020). The H2Ohio TAP conducted a thorough evaluation of the 40+ proposals received in response to the RFT and selected 10 technologies for further evaluation. The developers of these 10 technologies were given an opportunity to provide additional information and supporting data to allow an independent evaluation of their technology by a third party, Tetra Tech, Inc. (Tetra Tech).

As a contractor to Ohio EPA, Tetra Tech conducted an independent third-party evaluation of the 10 technologies selected by the H2Ohio TAP team. The goal of the evaluation was to provide a general assessment of the potential effectiveness, implementability, readiness, and cost of deploying each technology. Select technologies may eventually be demonstrated in the field under future H2Ohio programs.

2.0 PURPOSE

The primary purpose of the technology assessment and evaluations was to conduct a comprehensive scientific evaluation of the selected technologies to determine if and how they could be utilized to address HABs in Lake Erie.

Based on input from Ohio EPA and the H2Ohio TAP team, Tetra Tech established primary (P1 & P2) and secondary (S1 & S2) objectives for the third-party evaluation program. The primary objectives are critical to the technology evaluation and involve conclusions regarding technology performance that are based on quantitative and semi-quantitative data. The primary objectives for the evaluations of the participating technologies are as follows:

- P1: Effectively assess the performance, cost-effectiveness, and reliability data gathered from each vendor with regard to one or more of the 5 H2Ohio goals:
    - Reduce nutrient loading to rivers, streams, and lakes
    - Remove nutrients from rivers, streams, and lakes
    - Reduce the intensity or toxicity of algal blooms
    - Recover nutrients from animal waste
    - Improve nutrient removal in wastewater treatment systems, specifically with small (e.g., lagoon) and decentralized systems
- P2: Ensure that the evaluations are completed by appropriate personnel using a documented, consistent approach and level of detail, to include:
    - Proof of concept review
    - Fatal flaw analysis
    - Review of previous implementation of the technology or similar technologies
    - Review of data quality objectives
    - Review of quality assurance/quality control procedures and reports
    - Evaluation of scalability
    - Information gap evaluation
    - Evaluation of cost; both total and by unit, such as nutrient reduced/removed
    - Feasibility review for a proposed demonstration project
    - Feasibility review for full scale implementation
    - Statement of probability of success

The secondary objectives pertain to Tetra Tech's approach to assessing and presenting the information and thus support the primary objectives.

The secondary objectives for Tetra Tech's evaluation are as follows:

- S1: Prepare Comprehensive Scientific Assessment and Recommendations Reports for each technology that will support potential users' ability to make sound judgements on the applicability of the technology to a specific site and to compare the technology to alternatives.

- S2: Ensure that project deliverables follow consistent format and similar levels of detail. Each report will contain:
    - A summary of the technology and results of past uses of the technology;
    - Results of conceptual model review, fatal flaw analysis, and information gap evaluation;
    - A statement of probability of success and scalability of the project;
    - Verification of cost estimates at various implementation levels;
    - Results of the feasibility review for a potential demonstration project and full-scale implementation of the technology;
    - Verification of claims made by applicants.

The technology evaluation consisted of the (1) collection; (2) evaluation; and (3) summarizing and reporting of data on the performance and cost of each technology. These data provided the basis for meeting the primary objectives.

Most data supporting these evaluations were provided by the technology developers and Tetra Tech attempted to verify it using independent sources, when available. Tetra Tech focused its verification efforts on key aspects of the technology (e.g., effectiveness, cost) as well as any claims that seemed questionable. Otherwise, Tetra Tech assumed information provided by the vendor to be accurate. Instances where Tetra Tech is unsure of a claim being made by the vendor are noted in the report. In some cases, information was also obtained from the peer-reviewed scientific literature. Tetra Tech worked with each developer to obtain the data necessary to meet the primary and secondary evaluation objectives.

Tetra Tech then completed an independent evaluation of the data provided by each developer and prepared separate reports for each technology evaluation, following a consistent report format. This report provides a summary of our review of the Andersons Struvite DG® fertilizer.

3.0 TECHNOLOGY OVERVIEW

Struvite (NH4MgPO4·6H2O) is a soft phosphate mineral with a hardness of 1.5 to 2.0 Mohs and a specific gravity of 1.7. It is formed from a natural waste product that precipitates primarily out of sewage sludge and animal waste that can build up in sewer treatment works causing operational problems (Hammond et al., 2007). Struvite reclamation reactors have been installed at many wastewater treatment facilities globally, and are also being tested at livestock farms, food processing, and ethanol facilities. Talboys et al. (2015) indicate that recovered sources of phosphorus, such as struvite, extracted from wastewater have the potential to serve as a substitute for more soluble phosphate fertilizers (such as, monoammonium phosphate [MAP] and diammonium phosphate [DAP]). It is slightly soluble in water and readily soluble in acid. The water solubility of phosphate fertilizers depends on both acidic and neutral to alkaline conditions. Several factors also influence the application of phosphate as a fertilizer including rate of dissolution, soil characteristics, and plant species. The rate of dissolution has been found to increase as the particle size decreases and might be due to the finer particle size having a greater degree of contact time between the phosphate and soil (Samreen et al., 2019).

The Andersons currently process recovered struvite (wastewater treatment - sewage, livestock, food processing) and have the potential to synthesize struvite through various business partnerships in the U.S.

However, there is only about 10,000 tons of recovered struvite available to the Andersons in North America and at least 60,000 tons is needed annually for the Lake Erie watershed. The amount of synthesized struvite available for processing was not provided for evaluation. However, the Andersons are currently negotiating with providers of synthesized struvite. The Andersons have found that struvite material is most economically formed in an aqueous solution containing at least 50 parts per million (ppm) of soluble phosphate. When the pH of this solution is balanced, and both magnesium and ammonia are either present or added, the relatively insoluble crystals of struvite forms. This process allows for the efficient removal of soluble phosphorus from potentially harmful discharge , such as effluent from wastewater treatment systems. In addition to the struvite chemistry, the Andersons add an organic acid to create the dispersible granule (DG). The water dispersible chemistry is an additive to the struvite particles, that enables the larger agglomerated particle to disperse into tiny struvite particles using a lignosulfonate organic acid. Lignosulfonates are a byproduct formed in the pulping process as lignan that is removed from wood to form paper. Lignosulfonates organic acids are very effective in binding particles together yet are readily soluble in liquid water.

The Andersons technology is a bounded, granular material identified as Struvite DG®. The Anderson proposal claims that upon contact with water, each DG granule disperses into micro particles making it more efficient, due to its size, to move through the plant canopy into the root zone delivering nutrients with minimal nutrient loss and reducing runoff. Additionally, Struvite DG® has a very low fertilizer "salt index" (<8) compared to traditional phosphate fertilizers, such as MAP, making it very safe for direct applications at seeding. Struvite DG® is currently only used in specialty crops including turfgrass, home lawns, and commercial agriculture.

4.0 TECHNOLOGY EVALUATION

This section of the report addresses each of the criteria identified by Ohio EPA to be included in the independent evaluation process.

4.1 CONCEPTUAL MODEL REVIEW

The Andersons did not provide a formal conceptual model for review but have been researching and testing DG technology for more than 25 years; operate multiple processing and storage facilities; and have business partnerships with companies that provide recovered or synthesized struvite to manufacture their products. One of the Andersons struvite-based products currently on the market is SMARTPHOS DG® that is used on specialty crops such as turf, canola, and container grown nursery with the intent to move the technology into the agriculture market following additional research. The Andersons Struvite DG® technology was also selected as one of 16 technologies to participate in the U.S. Environmental Protection Agency (U.S. EPA), Office of Research and Development (ORD) and U.S. Department of Agriculture (USDA) sponsored NextGen Fertilizer Challenge in 2020 (U.S. EPA, 2020). The environmental and agronomic performance criteria evaluated as part of the U.S. EPA and USDA study include the following:

- **Environmental performance** by reducing nutrient losses to the environment through:
    - Reduced ammonia volatilization
    - Reduced nitrous oxide emission
    - Reduced nitrogen and phosphate runoff or leaching

- **Improve agronomic performance** by:
    - Not reducing yield
    - Not increasing net farm costs in terms of return on investment
    - Applicability to corn grown in the U.S. using existing application equipment

This study is ongoing and should provide data that will further assist in evaluating performance of the Struvite DG® technology in reducing nutrient loading in the Lake Erie watershed.

A separate study completed by U.S. EPA ORD in 2019, evaluated using wastewater-derived struvite as an alternative to conventional DAP fertilizer for crop production. The objectives of the study were to show how regulations drive system changes and how conventional wastewater treatment systems can be transitioned to more cost effective and sustainable alternatives using nutrient management. The study compared the emergy inputs for influent wastewater flow and nutrient levels, capital, and operational data from previous nutrient removal studies done by Ostara Nutrient Recovery Technologies, Inc. (Ostara). Emergy is defined as the available energy required directly and indirectly to make a product, process, or service. To evaluate the struvite application, this study utilized the Hydrologic and Water Quality System (HAWQS) software, which is a web-based interactive water quantity and water quality modeling system based on the Soil and Water Assessment Tool (SWAT). It enabled use of SWAT to simulate the effects of BMPs based on an array of crops, fertilizers, soils, natural vegetation types, land uses, and climate change scenarios and simulated the runoff of nutrients based on the type of crop, fertilizer quantity, and watershed characteristics. The simulation study was applied to a field located in Iowa (Theregowda et al., 2019).

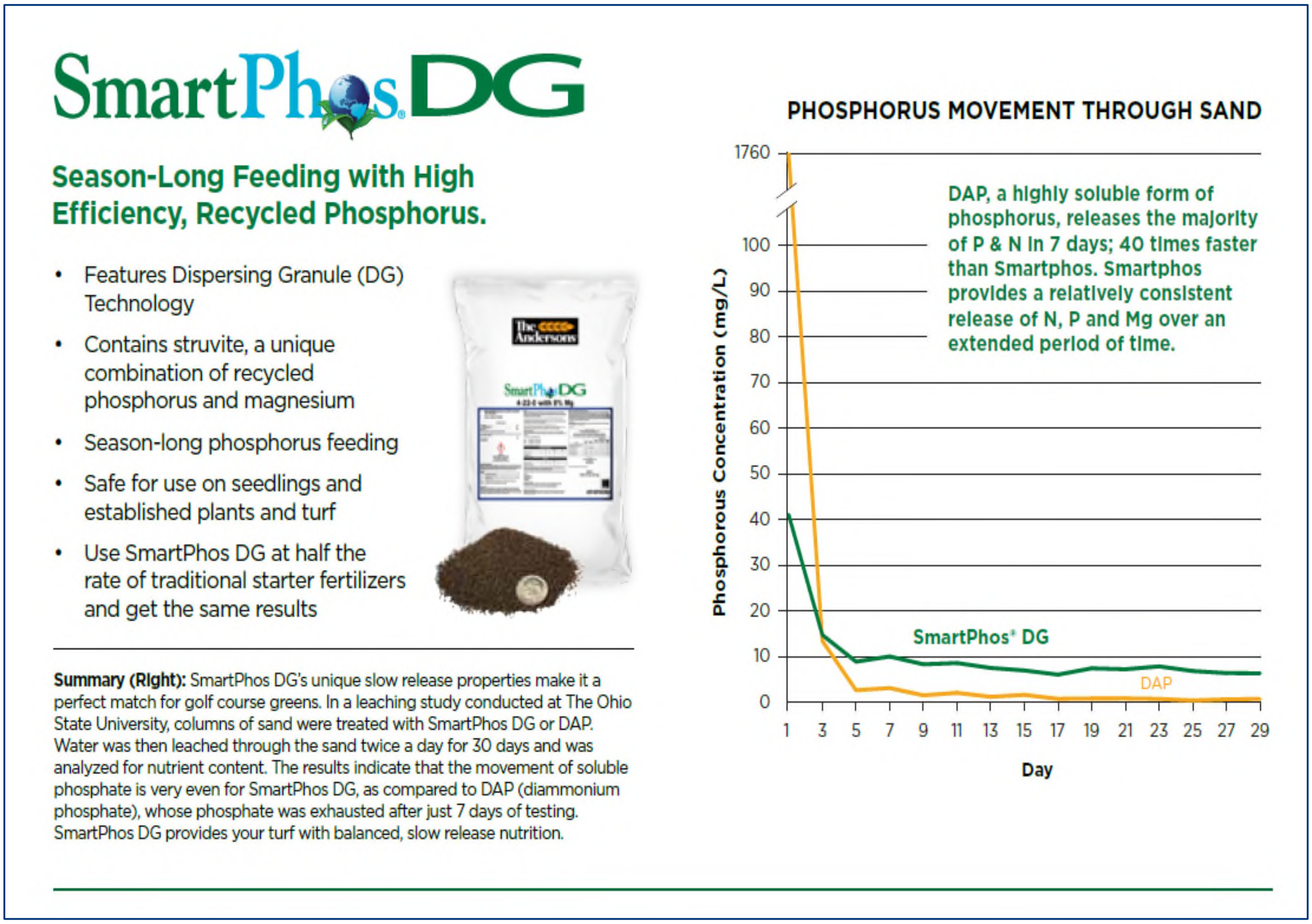
Key findings from the study are presented below:

- Precipitation induces increased runoff and the runoff of phosphorus for struvite was lower than the DAP.
- Crop yield does not vary long-term with the difference in type and quantity of fertilizer application, which has been proven previously through greenhouse pot studies.
- The slower rate of phosphorus release from struvite granules reduced plant uptake of phosphorus during early growth but without detriment to crop yield.
- Stringent nutrient reductions lead to tradeoffs that should be further evaluated in order to choose the most sustainable treatment alternative.
- Application of struvite as a substitute or replacement to traditional phosphate fertilizers for crop growth over a long period of time can lead to substantial phosphorus and overall emergy reduction.
- Overall, DAP had an order of magnitude higher total emergy relative to struvite and bigger environmental footprint.

The Andersons H2O proposal documents that through their research over the past several years, the enhancement of struvite by reducing its particle size through granular engineering (DG technology) provides greater efficiency with soil-based agronomic and environmental benefits. Some of these agronomic benefit claims include (1) engineered particle shapes and sizing for precise application and/or blending, (2) rapid phase-change in the field with liquid water (irrigation or precipitation); (3) increase in surface area of the insoluble agronomic component, making the material more efficacious; and (4) rapid penetration into the soil matrix, leaving no granules on the soil surface. Previous demonstrations to support the agronomic claims and an environmental fate and transport study is further discussed in Section 4.3.

The Andersons commercially produce a DG product identified as SmartPhos DG® (Figure 1). They currently have facilities in four locations, processing over 200,000 tons of this product annually. The production of its struvite is a 2-step process (1) recycle or synthesize chemical struvite and (2) granule engineering into a "dispersible form" as noted in the Andersons Struvite DG® proposal.

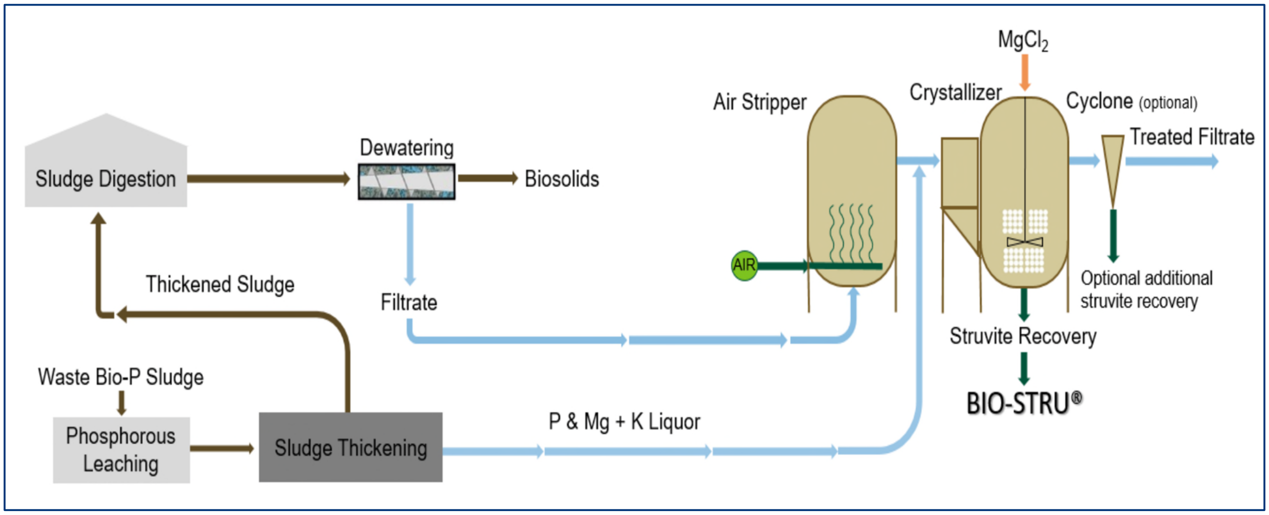
Figure 1 - Struvite-based SmartPhos DG®



4.1.1 Struvite Recovery

Struvite recovery from wastewater treatment (sewage, livestock, food processing) for the Andersons® current operation is about 10,000 tons per year with the potential for expansion with the increasing number of supply chains becoming available. The current providers for struvite recovery in the U.S. include Ostara, Schwing Bioset, Inc., and Cenetrisys. Figure 2 presents an example configuration of a Schwing Bioset struvite recovery process. There are various design configurations to consider that are dependent on a number of factors that may include water chemistry, biosolid dewatering, grain size versus mass of struvite recovered, footprint of existing wastewater treatment facility, and output requirements.

Figure 2 - Schwing Bioset Example Struvite Recovery Process



Ostara has the highest number (18 locations) of struvite recovery facilities currently operating in the United States and has completed pilot testing studies for struvite recovery. A pilot study was completed at the Clean Water Services Durham Advanced Wastewater Treatment Facility located in Durham, Oregon to document reduction of nutrient loading to the nearby Tualatin River. The Durham Plant discharges directly into the Tualatin River and applies strict phosphorus removal limits of 0.1 milligrams per liter (mg/L) in the treated effluent. Sludge fermentation provides an organic substrate to feed biological nutrient removal. However, 30 percent of sewage works inflow phosphorus and ammonia comes from the sludge dewatering return. The study found that struvite precipitation for phosphorus recovery can remove this return phosphorus flow, thus improving biological nutrient removal performance and loading to the river. The 8-week pilot study of the Ostara reactor at the Durham plant treated about 1/300th of the plant's capacity and reported that full-scale performance could be expected within the current footprint of the plant (CEEP, 2008).

4.1.2 Struvite Synthesis

Ostara currently operates a full-scale commercial struvite manufacturing facility that can synthesize the material through a proprietary process. Availability and capacity of the facility to process struvite was not disclosed. The added benefit of this facility is that it can complete both synthesis and engineering granulation into the DG process in a single facility allowing further expansion of the Andersons current production. Ostara recently announced plans to construct a second struvite synthesis facility located in St. Louis, Missouri which will could further increase supply (Woodroof, 2021).

4.1.3 Converting to Struvite DG®

The granular processing for the Andersons can be completed through one of their business partnerships or at their existing facilities located in Maumee, Ohio, Carey, Ohio, Seymour, Indiana, or Mocksville, North Carolina. The existing Andersons facilities granulate struvite primarily for the turf market and limestone and gypsum for the agriculture market. The facilities do not require any upgrades to process more struvite but would require discontinuing and/or relocating some of the current Ohio processing operations to another facility to account for any additional demand.

The process of converting to a "DG" starts with grinding struvite to roughly minus 100 mesh particle size, conveying to a pan-granulator where liquid organic lignan binder is added, which agglomerates the particles back into a granule. The "wet" granules are then conveyed to a dryer to remove excess moisture, cooled, and screen the granules to size. The lignan binder (specifically lignosulfonate) is an organic acid that is generated from removing lignan from wood processing. It is essentially a by-product and is usually complexed with ammonia or calcium. The dried granules are applied using traditional agriculture equipment, but break-down into tiny particles again once they contact liquid water in the field (Figure 3). It is important to note that the particle is "dispersible" and not soluble.

Figure 3 - Basic DG Application

4.2 FATAL FLAW ANALYSIS

A fatal flaw analysis was not submitted as part of the Andersons proposal for Struvite DG® so a limited fatal flaw screening was completed based on the technology limitations identified during the assessment process and summarized throughout this report. Only the criteria that require further evaluation or clarification for meeting the goals and objectives of the H2Ohio program were considered and are summarized in Table 1 along with a potential response to address the limitation/flaw identified.

Table 1 - Fatal Flaw Screening – Struvite DG®

Criteria	Limitation/Flaw	Potential Response to Address Limitation/Flaw
Evaluation of Cost	Did not provide a direct cost comparison to traditional acidulated rock phosphate fertilizers, such as MAP or DAP	Highlight other long-term cost benefits: • Projected revenue from Struvite DG-based fertilizer. • Reduction of BMP costs to farmers/landowners. • Return on investment for wastewater treatment plant upgrades to reduce equipment fouling.

Criteria	Limitation/Flaw	Potential Response to Address Limitation/Flaw
		Energy savings for processing compared to traditional fertilizers.
Scalability/Supply Chain	1. Limited number of struvite reclamation suppliers 2. Has only been applied at small scale (greenhouse and local farm)	• Provide more details on other struvite sources or availability of synthesized struvite. • Evaluate option to import vs reclaiming struvite in U.S., if available in limited supply. • Evaluate at larger scale under various scenarios native to Ohio soil types, crops/yield, and watershed conditions.
Environmental Fate and Transport of Nutrients at Large Scale	Leaching studies only completed at bench-scale or greenhouse pot studies	• Simulate through modeling under various scenarios native to Ohio soil types, crops, and watershed conditions. • Evaluate at larger scale under various scenarios native to Ohio soil types, crops, and watershed conditions to evaluate runoff/leaching.

4.3 REVIEW OF PREVIOUS IMPLEMENTATION OF STRUVITE DG®

The following sections present a summary of past demonstrations of the Andersons Struvite DG® technology or similar struvite technology applications completed by university researchers in collaboration with the Andersons or by the Andersons internal researchers.

4.3.1 Fertilizer Granule Dissolution Study

This 2010 study was conducted by Ohio State University research associates Dayton et al. (2010) through an Ohio Department of Development Grant to evaluate the dissolution rates of MAP, DAP, the Andersons Struvite DG®, and struvite (non-DG). The bench-scale study was completed over a 30-day period to evaluate the leaching concentrations of phosphorus, magnesium, nitrate, and ammonium in the four different granule materials (Dayton et al., 2010).

Analytical data for ammonium, nitrate, phosphorus, and magnesium versus volume leached over the 30-day period was plotted using the average of duplicate samples for the four granule materials. The plots reported in the study showed higher solubility for MAP and DAP as compared to struvite (non-DG) and Struvite DG®. The ammonium results showed that greater than 99% of nitrate was leached for both MAP and DAP, while less than 10% of nitrate was leached from Struvite DG® and struvite (non-DG). The phosphorus results for MAP and DAP showed that phosphorus was leached at a slightly slower rate than nitrate. This was reportedly due to secondary precipitation of phosphorus with trace cations in solution, such as calcium. With the exception of day 1 of the study, both Struvite DG® and struvite (non-DG) showed similar dissolution rates for nitrate, phosphorus, and magnesium indicating that struvite was the mineral phase controlling nitrate and phosphorus solubility throughout the 30 days of leaching. The report concluded that the two struvite materials used for this study exhibited solubility characteristics that could make these products less susceptible to loss from leaching and runoff, but field applications were needed to confirm the results (Dayton et al., 2010). The low solubility characteristics of struvite have also been documented in a greenhouse study on sandy soils completed by Vaneeckhaute et al. (2015).

4.3.2 Column Study to Evaluation Leachate Transport Risk of Struvite DG® vs MAP

The objectives of this 2021 Ohio State University study were to evaluate the solubility and leaching potential of nitrogen, phosphorus, and magnesium for the Andersons Struvite DG® material compared to MAP. The column test was completed in accordance with U.S. EPA Method 1314 (see Figure 4), Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using an Up-Flow Percolation Column Procedure, which is a part of the U.S. EPA Leaching Environmental Assessment Framework. This test provides data about liquid/solid partitioning (transport) for inorganic or non-volatile organic constituents. The method provides eluate nutrient (nitrogen, phosphorus, and magnesium) concentrations and is intended to demonstrate leachate transport under field conditions. Figure 4 shows the column test set up. Each flow through column test was run for approximately 2 weeks. The column tests were completed on four different Ohio soil types (sandy, clay, organic, and loam) potentially relevant to nutrient (nitrogen and phosphorus/magnesium) liquid/soil partitioning (transport) (Dayton, 2021).

Figure 4 - U.S. EPA Method 1314 Column Set-up

Soil properties relevant to nutrient transport that were evaluated include pH, electrical conductivity, organic carbon, cation exchange capacity, and soil texture (clay). For each column study, (1) nutrient (nitrogen, phosphorus, and magnesium) concentrations and cumulative mass released vs test soil properties relevant to nutrient transport were plotted and (2) eluate nutrient (nitrogen, phosphorus, and magnesium) concentrations and cumulative mass release vs cumulative liquid/solid ratio for each Ohio soil type were also plotted. The liquid/solid ratio is the fraction of the total liquid volume (eluate) to dry mass equivalent of the solid material (soil). This allowed for comparisons between Struvite DG® and MAP (Dayton, 2021). The treatment results are summarized below.

Cumulative release of nutrients vs soil properties results:

- Cumulative release of magnesium showed little relationship with soil properties. The MAP treatment had slightly higher magnesium levels than the Struvite DG® treatment. Considering there is no magnesium in MAP, the release was reportedly due to cation exchange.
- Cumulative nitrogen release for the MAP treatments were higher than for the Struvite DG® treatments. However, there was no apparent effect of soil properties on nitrogen release.
- For phosphorus, the MAP treatments showed considerably greater release than the Struvite DG® treatments. However, soil properties had no apparent effect.

Cumulative release of nutrients vs liquid/solid ratio results:

- The cumulative release of magnesium over time were similar for Struvite DG® and MAP treatments, though MAP treatment concentrations were consistently higher.
- Nitrogen concentrations were reported as being similar for both Struvite DG® and MAP treatments, though generally higher for MAP treatments. For sandy soil, MAP treatments released considerably more nitrogen than Struvite DG® treatments.
- For MAP treatments, phosphorus concentrations spiked early and then declined, while Struvite DG® treatment concentrations remained fairly consistent and considerably lower overall than for MAP treatments across the four soil types. Again, the sandy soil released more phosphorus from the MAP treatments.

The study concluded that the MAP treatments released more nutrients than the Struvite DG® treatments for all four soil types. The study also found that the benefits of using a slow-release fertilizer, such as Struvite DG® treatment, were evident across time and each soil type, especially for sandy soils that may have a greater risk of nutrient transport (Dayton, 2021).

4.3.3 Greenhouse Phosphorus Efficiency Study

The Andersons completed an internal greenhouse study that involved growing corn in pots using native soil from Wood County, Ohio. The objective of the study was to observe the environmental fate of the Anderson Struvite DG® technology compared to traditional DAP fertilizers. Researcher Amy Schroeder planted corn in 1-gallon pots with 5 replicates in a randomized design, of each treatment comparing Struvite DG® to the DAP fertilizers. This trial was run utilizing native Wood County, Ohio soil with naturally occurring phosphorus at 13 ppm that was determined prior to the study. The level of phosphorus (13 ppm) was considered in the study for determining fertilizer concentration rate for testing. Fertilizer was applied to increase the phosphorus level to 15 ppm in each pot, which was reported as the critical level of phosphorus for corn growth based on the Tri-State Fertilizer Recommendations (Tri-State Fertilizer Recommendations, 2020).

During the study, leachate samples were collected from the bottom of each pot at 15, 30 and 45 days after treatment and consisted of a composite of all replicates. The concentration of phosphorus in the leachate sample collected from the Struvite DG® pot was found to be below the detection limit of 0.20 ppm as compared to the DAP fertilizers tested. The DAP fertilizers initially had concentrations of phosphorus ranging from 2 to 4.75 ppm in leachate samples collected during the 15 day sampling event, but concentrations were reduced to 1 to 2 ppm during the 30 day sampling event. Plant growth was relatively similar between the Struvite DG® and DAP fertilizer treatments during the later stages of the study (30 to 45 days testing period).

A study done by Talboys et al. (2105) indicated that mixtures of struvite granules and more soluble acidulated rock phosphate fertilizers can provide a more sustainable fertilizer strategy than the sole use of either fertilizer by maximizing early crop development and also supplying phosphorus at later stages of plant development due to the lower solubility of struvite granules. The study also indicated that further field demonstrations are needed to assess the effectiveness of these strategies under a wider range of soil types and crop systems.

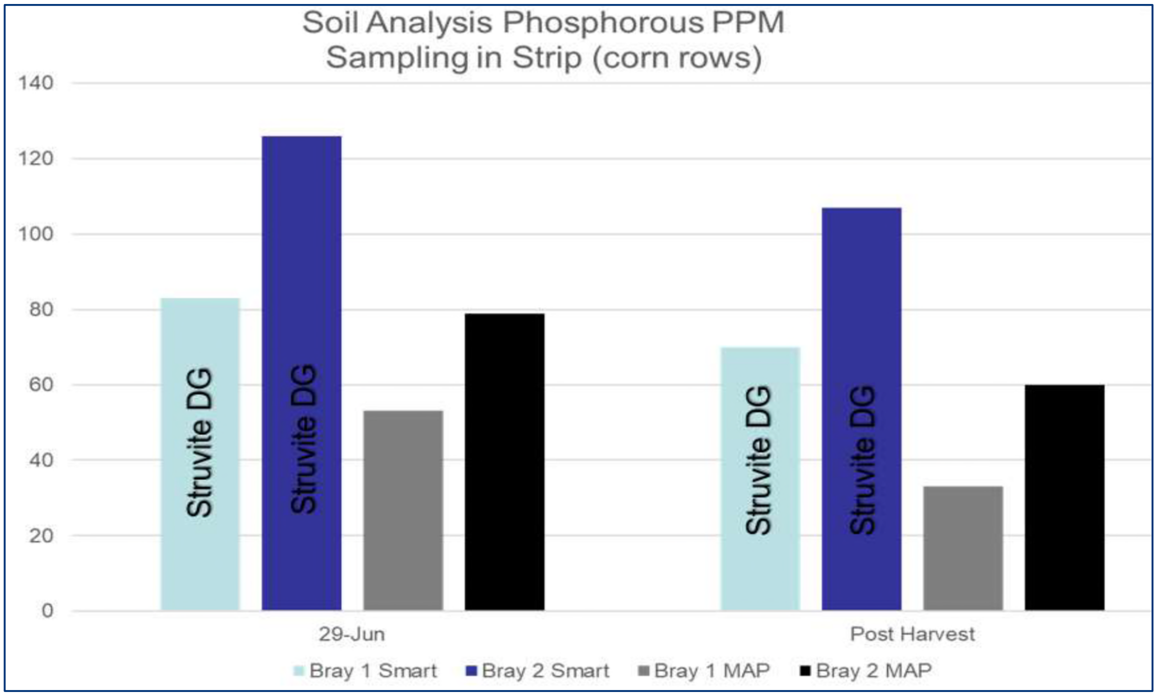
4.3.4 Struvite DG® Corn Crop Application in Lake Erie Watershed

In the Fall of 2012, the Andersons solicited a customer-farmer in Gibsonberg, Ohio to apply Struvite DG® to their corn crop, on property that is located in the Lake Erie watershed. The farmer applied Struvite DG® to a 40 acre corn field using strip-till application. The applications were alternated between two corn varieties, and two phosphorus treatments. The Struvite DG® was applied at half the rate of phosphorus pentoxide vs the rate of MAP in the same field. The following year, the field was harvested, and the results reportedly yielded very similar results between treatments for bushels/acre of corn for both Struvite DG® (171 bushels) and MAP (170 bushels).

The farm study was repeated in 2016-2017 using the same strip-till equipment. During this study, Struvite DG® was applied to about 64.54 acres vs about 47.43 acres for MAP. The following year, crop yield was reported as 173.5 bushels/acre for Struvite DG® and 176.66 bushels/acre for MAP.

Following the above harvest year, the farmer collected core soil samples directly in the nutrient strip lanes. The results showed higher results in the field where Struvite DG® was applied compared to the MAP (see Figure 5).

Figure 5 - Core Sample Results - Nutrient Strip Lanes

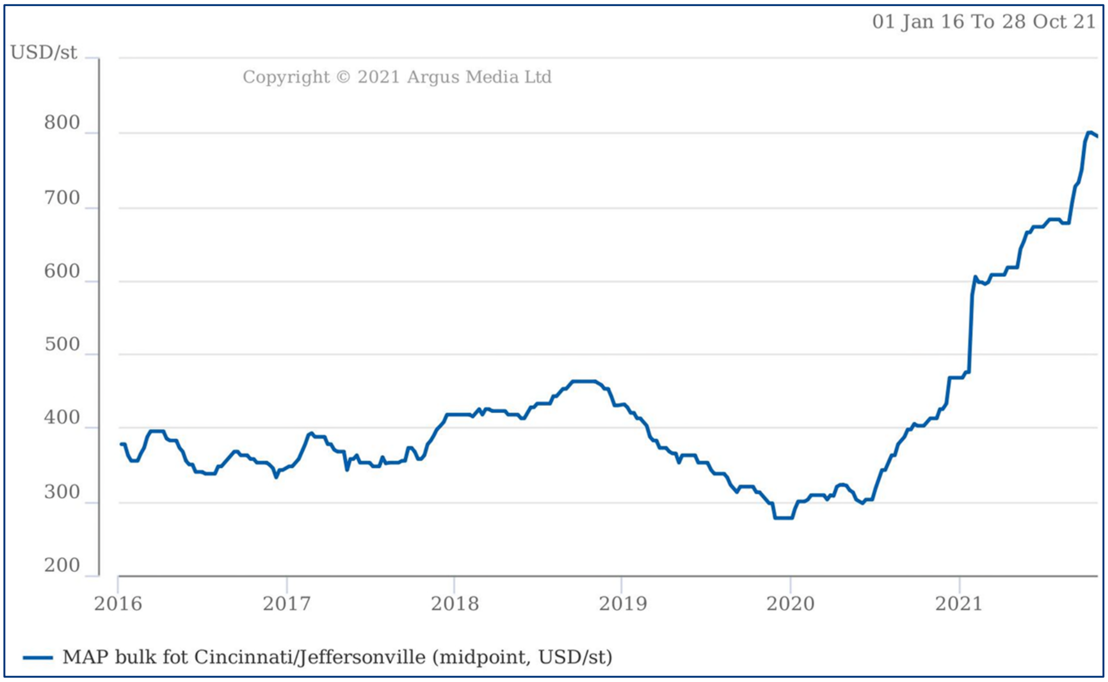


4.4 COST EVALUATION

Tetra Tech relied primarily on literature reviews for evaluating costs associated with struvite recovery, processing, and distribution. Of these three, struvite recovery represents the biggest costs and includes research/pilot testing, siting, capital equipment, additional chemicals and dosing of caustic and magnesium, and operations and maintenance associated with infrastructure upgrades to existing wastewater treatment systems. However, researchers have estimated that cost savings can be achieved with struvite recovery processes that range from $500 to $2,500 for every 260,000 gallons of wastewater treated. These savings are associated with reduced maintenance and materials used to remove struvite scaling that can cause operational problems and system downtime. The return on investment is reported to be about five to ten years for a 14.5 million gallons per day facility (Bird, 2015).

Detailed cost data associated with processing and distribution for the Andersons Struvite DG® technology was not provided. However, Ostara has 18 recovery facilities operating in North America and its first synthesis facility recently opened in Florida with another location planned for construction in St. Louis, Missouri. If selected to support the H2Ohio program, the Andersons plan to license Ostara to assist in manufacturing Struvite DG® product at this facility. This facility was identified as a turn-key option as the Ostara facility in Florida is already operating and shipping struvite product. The additional benefit to this Ostara option is that synthesis and granulation processing occurs in one facility. The Andersons also operate two granular processing facilities in Ohio located in Maumee and Carey, Ohio. The facilities do not require upgrades but would need to discontinue some production to process the additional volume that would be required for the Lake Erie watershed. Costs for processing and storage can range from approximately $150-$175 per ton for struvite compared to $40-$50 per ton for processing limestone for agriculture lime applications at these facilities (not related to phosphate production), excluding dealer margin. The total estimated costs reported by the Andersons for recovered struvite, processing, and distribution over the past five years has ranged from $800-$1,200 a ton.

Figure 6 - MAP Bulk Costs in Select Ohio Cities 2016-2021



In comparison, the cost of DAP fertilizer has ranged from $410-$776 a ton over the past ten years (Schnitkey et al., 2021). Note that price fluctuations with phosphates as noted in Figure 6 graph shows the difficulty in comparing Struvite DG® and MAP, however, the price difference between the two has typically been relative to commodity prices and struvite has been more expensive relative to MAP. Table 2 presents a comparison of estimated costs and benefits of Struvite DG® compared to MAP based on a 100-acre cropland field.

The cost of transportation was also identified as an additional cost due to the limited number of struvite suppliers located near the Andersons processing and storage facilities in Ohio.

Table 2 - Comparison of Estimated Costs and Benefits of Struvite DG® Compared to MAP

Categories for Comparison	Baseline (Free Drainage)	MAP	Struvite DG®	Difference Between MAP and Struvite DG®
Total installation cost of system	Not applicable	$39 per acre & $3,900 per 100 acres	$50 per acre & $5,000 per 100 acres	$ 11 per acre and $1100 per 100 acres
Estimated yield increase per year (one farm in Ohio study – 2 years)	Not applicable	N/A	Two studies yielded 1.2 bushels less	(1.2)

Categories for Comparison	Baseline (Free Drainage)	MAP	Struvite DG®	Difference Between MAP and Struvite DG®
Average yield per acre (2020 Iowa)	178 bushels per acre	181 bushels per acre	184 bushels per acre	3 bushels per acre
Price per bushel (March 2021 Ohio)	$4.89	$4.89	$4.89	Not applicable
Annual dollar value of increased yield	Not applicable	N/A	1.2 * $4.89 = $5.86	($5.86) per acre & $586.00 per 100 acres
Years for yield increase to cover implementation costs of system	Not applicable	N/A	N/A	Yield increase will not cover the cost to implement

Note: This comparison of estimated costs and benefits of Struvite DG® (mid-2021 price $870 to 970 + $80 retail margin = $1,000 average) compared to MAP (mid-2021 price in the eastern corn belt $670 to $730 + $80 retail margin = $780 average) (Based on a 100-Acre Cropland Field and Using Average Figures from 2021 for "Corn for Grain"). Assumes 100 lbs. per Acre Application of MAP.

4.5 SCALABILITY EVALUATION

The Andersons currently provide Struvite DG® products, such as SmartPhos DG®, to the turf and specialty markets, with no struvite production currently in the agriculture market. The Andersons receive struvite from two primary providers (Ostara and Schwing Bioset) through recovery and synthesis and can process into a "DG" at an estimated 200,000 tons annually. However, only about 10,000 tons of struvite is recovered through wastewater treatment system reactors currently operating in North America so reliance on synthesized struvite would be required to meet the demands for the Lake Erie watershed. The Andersons have estimated a minimum of 60,000 tons of struvite material annually would be required to treat the highest nutrient-impacted areas within the Lake Erie watershed.

The Andersons have received struvite for processing from multiple wastewater treatment facilities in the past and are currently negotiating with other suppliers if the demand increases as a result of the Lake Erie watershed H2Ohio program. Synthesized struvite material would also be utilized and provided by Ostara's location in Florida or other available facility and transported to one of the Andersons storage facilities in Ohio. The struvite can also be granulated at the Andersons two existing processing facilities located in Carey and Maumee, Ohio. SMARTPHOS DG® is currently produced at the Maumee, Ohio facility at an estimated rate of 3 tons/hour, which is an acceptable rate for the turf markets; however, this rate would not meet the demands for the Lake Erie watershed. For the Lake Erie watershed, processing would also be completed at the Andersons facility located in Carey, Ohio that mainly granulates limestone and gypsum for the agriculture markets. Granulation throughput at the Carey facility is estimated to be about 20 tons/hour. The granular processing facilities would not require any scalability upgrades.

The Andersons two existing distribution facilities currently serve the northwest Ohio agriculture community and have 100,000 tons of dry fertilizer storage capability in Maumee and another 30,000 in Toledo. Storage capacity at these two facilities can meet the demands for the Lake Erie watershed.

The biggest limiting factor is output due to the limited number of struvite recovery facilities available in the U.S. to meet the demands of the Lake Erie watershed. The Andersons and its business partners are in the second phase of research and development in addressing phosphorus recovery and recycling limitations. Ostara has multiple struvite recovery facilities that have transitioned to full-scale operational processes in wastewater treatment facilities in other countries. Available literature also indicates that struvite recovery systems upgrades are not possible at all wastewater treatment facilities, such as those with membrane bioreactors or aeration systems that do not have digesters (Bird 2015).

4.6 INFORMATION GAP EVALUATION

Based on the Andersons proposal and Tetra Tech's literature review, there is limited information on (1) the environmental fate and transport of nutrients when applying struvite at large-scale compared to conventional acidulated phosphate rock fertilizers and (2) its effectiveness when applied at large-scale with a comparison to conventional acidulated phosphate fertilizers for crop yield in Ohio. Most of the available literature provides information regarding treatment effectiveness in greenhouse pot studies or smaller land applications. There is also a lack of information regarding the long-term performance of struvite application longevity, and seasonal variations that may influence treatment since HABs are more likely to occur in the summer months (June, July, and August). An evaluation under various scenarios native to Ohio soil types, crops, and watershed conditions is recommended.

The SWAT watershed modeling completed by U.S. EPA ORD in 2019 at a study area in Iowa, provided another tool that could assist in planning prior to full-scale implementation of this technology. Applying the SWAT or similar watershed model for the Struvite DG® technology for a study area in Ohio could provide simulation data for evaluating runoff of nutrients for the types of crops expected, fertilizer quantities, and soil and applicable watershed characteristics. This additional data along with the data expected from the U.S. EPA and USDA NextGen Fertilizer Challenge would provide important information for its application in the Lake Erie watershed.

A more detailed economic analysis for a larger scale application of the technology was also identified as a significant data gap. Some cost data for the capital equipment plant upgrades, operations and maintenance costs, chemical additives is available from past studies through literature reviews but a more comprehensive comparison of the sustainable long-term cost factors, such as those listed in the U.S. EPA ORD 2019 study are limited. Cost factors for further evaluation should include revenue generation from fertilizers, reduction of equipment fouling from precipitation of struvite, meeting regulatory discharge limits, and overall energy cost savings compared to traditional fertilizers.

4.7 FEASIBILITY FOR LARGE-SCALE TECHNOLOGY DEMONSTRATION

A large-scale technology demonstration is feasible with the Andersons Struvite DG® technology. They have existing struvite providers and their own processing and storage facilities located in Ohio with the ability to increase production as demonstrated through their current production of SMARTPHO DG® that is used in the turf market. A modeling of the proposed demonstration area in Ohio on a large-scale to simulate the expected effects of nutrient runoff and other design factors under different scenarios would be beneficial to the Andersons prior to the technology demonstration. The technology has only been applied at small-scale to date.

If the Andersons were to receive support for a large-scale Struvite DG® demonstration project, their preference would be to apply 1,000 tons across a multitude of 18-20,000 acre fields in selected areas and monitor nutrient loading and crop yield effects. To be most effective, this demonstration would be completed during more than one season on a multitude of soil and crop types. It may even be best to solicit agriculture extension for farms considered to be highest environmental risk. Funding would be managed between Ohio and the volunteer farms, and the Andersons would work with local farmers to deliver the Struvite DG®. There would be no cost increase to farmers for applying Struvite DG® to their fields in a properly designed multi-year cooperative funding agreement, which also could include other contributing partner agencies and organizations that share concerns for the Lake Erie Basin and producer adoption of innovative conservation technologies and approaches. Ohio should also consider funding monitoring of farm fields for yield and environmental impact through Ohio State University and/or Heidelberg, or other relevant organizations.

4.8 FEASIBILITY FOR FULL-SCALE IMPLEMENTATION

Previous studies summarized in Section 4.3 and data obtained through literature reviews demonstrate that this technology has the opportunity for success in addressing nutrient loading issues that are contributing to the Lake Erie HABs, if applied on a large-scale. The processing and use of recovered struvite-based fertilizer through phosphorus precipitation has been proven as a sustainable option compared to use of traditional acidulated rock phosphate fertilizers. Past studies also show that with mixed proportions of application with other high soluble phosphate fertilizer, struvite has the potential to reduce extraction of phosphate rock for commercial fertilizer manufacture and provide wastewater treatment facilities with revenue generating economical options that meet nutrient regulations. Further data and regulatory incentives may further demonstrate the economic and environmental benefits of nutrient recovery in the agriculture market.

4.9 PROBABILITY OF SUCCESS

Previous studies of the Andersons Struvite DG® and similar studies with other struvite-type fertilizers demonstrate that this technology can assist in reducing nutrient loads that are contributing to the Lake Erie HABs, if applied on a large-scale. As indicated in Section 4.3, the Andersons have demonstrated success in testing the effectiveness of their product through bench-scale and greenhouse pot studies, and a small-scale field application at a farm field located within the Lake Erie watershed. The probability of success is therefore high if it can be deployed at sufficient scale with a continuous source of struvite and will also be dependent on the financial incentives offered to landowners/farmers and their greater awareness of the long-term sustainability of this technology and positive crop yield impacts.

4.10 FINANCIAL VIABILITY

The Andersons was established in 1947 and is headquartered in Maumee, Ohio. The company has been a publicly-traded company on NASDAQ since February 1996. At the end of 2020, sales were $8.2B with adjusted earnings before interest, taxes, depreciation, and amortization (EBITDA) of $225M and total assets of $4.2B. Not only are the Andersons a financially viable institution, but they have a long history of being an integral part of the global food supply chain. The Andersons formulate, store, and distribute approximately two million tons of dry and liquid agricultural nutrients through an extensive dealer network. They own and operate more than 70 grain terminals across the U.S. and Canada, with a combined total storage capacity of over 216 million bushels. These grain facilities accept corn, soybean, wheat, and other commodities.

4.11 QAPP

The Andersons did not provide raw data to support the past technology studies completed (see Section 4.3) and therefore no Quality Assurance Project Plan (QAPP) was provided. Information about the performance of the Struvite DG® technology was obtained through reports completed by Ohio State University researchers that worked in collaboration with the Andersons or through the Andersons internal studies. Most of the research was completed at bench-scale or in greenhouse pot studies on leaching and runoff characteristics with one farm field study that evaluated crop yield and nutrient retention in soil. The data collected through Ohio State University are assumed to be of high quality and the leachate column testing was completed in accordance with EPA-approved methodology (Method 1314).

The most stringent third party testing will be completed during the U.S. EPA ORD and USDA NextGen Fertilizer Challenge, but data has not been provided for this study.

4.12 DATA VALIDATION

Data validation and quality assurance/quality control checks are not mentioned in the original technology submission for the Andersons Struvite DG® technology. However, the data reported by Ohio State University and used to prepare a portion of this evaluation are considered to be validated.

4.13 SUPPLY CHAIN

The Anderson Struvite DG® technology relies on resources that are supply chain dependent and currently process about 10,000 tons of struvite annually. The technology requires struvite chemical reclamation and\or synthesis that are available in limited quantities and locations across the U.S. The Andersons currently obtain struvite from multiple facilities, including Ostara and Schwing Bioset, but are currently negotiating with additional suppliers to meet the estimated supply demands (60,000 tons) for the Lake Erie watershed situation. The process also requires sourcing of ammonia and magnesium with no supply chain risks identified. Additionally, transportation of struvite by rail and/or truck to Ohio is a critical portion of the supply chain. Distribution to the Ohio farm dealer network is also a critical last step in the supply chain but the Andersons have storage facilities located in northwest Ohio, so no distribution risks were identified.

4.14 ENVIRONMENTAL RISKS

Past studies completed for Struvite DG® show lower risks to the environment when compared to more soluble acidulated rock phosphate fertilizers. The past data provided shows that there is a slower rate of plant phosphorus uptake during the growing season as compared to acidulated rock phosphate fertilizers, such as MAP or DAP, with no impact on crop yield. The core samples also collected from the nutrient strip lanes during the Ohio farm study completed by the Andersons showed that the Struvite DG® retained higher concentrations of phosphorus compared to the MAP one year following the crop harvest thereby reducing runoff. Struvite DG® can be implemented in the same manner as traditional fertilizers and provides a more sustainable fertilizer management strategy especially during the later stages when plant growth is at its peak providing a residual source of phosphorus and reducing the environmental footprint.

The chemical makeup of the binding agent used as part of the granular struvite processing is lignosulfonate. Lignosulfonate is currently exempt from the U.S. EPA Toxic Substance Control Act (TSCA) chemical substance inventory list.

4.14.1 Health & Safety

It is unlikely that implementation of the Struvite DG® technology poses a significant risk to the health and safety of those applying the material to farm fields. The application technique is compatible with current agricultural machinery and practices used for common large-scale production such as planters, fertilizer applicators, or tillage equipment. As with most farming applications, wearing personal protective equipment (PPE) is necessary to reduce inhalation risks.

4.15 COMMUNITY PERCEPTION & DISPROPORTIONATE IMPACT

Limited information is available to assess the community acceptance of this technology, but it is expected to be positive with no disproportionate impacts. Providing a more sustainable fertilizer through use of reclaimed struvite material and reducing the nutrient loading runoff is seen as a necessary step towards reestablishing a quality watershed within the Lake Erie region. Continued community involvement and regulatory agency support will be necessary for long-term success.

4.16 WASTE/BY-PRODUCT MANAGEMENT REQUIREMENTS

There are no waste and/or by-product management requirements that will impact the implementation of Struvite DG®. The struvite material is recycled from wastewater streams that precipitates out of sewage sludge and animal waste. Struvite fertilizer is also reported as having no pathogens, heavy metals, or radionuclides unlike phosphate rock ores (Bird, 2015).

5.0 FINDINGS AND OPINIONS

Based on a review of the available information and correspondence with the Andersons, Tetra Tech has the following conclusions regarding the Struvite DG® technology:

- The technology is effective at reducing nutrient loading as demonstrated through the dissolution and column tests, and greenhouse leaching and runoff studies on a small scale. However, the technology has not been field tested to determine environmental fate and transport of nutrients under different scenarios on a larger scale in Ohio.

- The greenhouse pot and independent farm studies showed that the slow rate of phosphorus release from struvite granules reduces runoff and plant uptake of phosphorus during the early stages of growth but continues to provide a phosphorus source during the later stages of plant growth without detriment to crop yield. Additional research is needed on how Struvite DG® performs at controlling nutrient loads and maintaining crop yield on a large scale with soil types and crops native to the Lake Erie watershed.

- The cost of struvite ($800 to $1,200/ton) is significantly higher than traditional acidulated rock phosphate fertilizers due to the limited availability of struvite reactors and added cost of transportation. A more comprehensive economic analysis of long-term costs is recommended to evaluate projected revenue generation from reclaimed struvite fertilizer, reduction of equipment fouling issues due to precipitation of struvite, reducing BMPs and meeting regulatory discharge limits, and overall energy cost savings that would provide data to determine cost/pound of phosphorus removed.

- The biggest gap identified for scalability of the technology was the limited supply chain of reclaimed struvite to process into Struvite DG® that would be required to support the Lake Erie watershed. However, the Andersons are negotiating with other struvite reclaimers in anticipation of meeting the supply demands.

- Potential barriers to widespread adoption of Struvite DG® is cost differential without incentives, which could be further evaluated through a pilot project funded by H2Ohio.

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