APSC 169 (Fundamentals of Sustainable Engineering Design)

Struvite Based Reactor for Phosphorus Reclamation and Application

Final Project Report

Group T2I-2 /

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Mission Statement

AGIS seeks to bring together creative and innovative designs to end-users to create both unconventional but also highly accurate systems that solve the problems that seem too big to tackle.

1 Executive Summary

After reviewing current research on farm manure applications and the means of waste management systems AGIS has developed a setup, implementing a nutrient-reclamation based system to separate liquid and solid waste to reclaim the nutrients in the form of struvite, a crystal that can be utilized as a premium fertilizer or sold as a commercial product. On-farm manure storage systems tend to stockpile over winter and run-off seasons. Due to a lack of storage, this excess manure is spread onto the field in mass; Before the nutrients can be absorbed into the crops, rainwater flows through the fields, collecting the nutrients and polluting lakes. By taking the excess manure and reclaiming its nutrients, farmers will not have to distribute high phosphorus concentration manure onto the crop field during run-off seasons just to later be swept away into lakes. The components of this report and system proposal will cover:

- Liquid manure management on moderate and large-scale animal agriculture farms
- Seasonal application of manure and waste storage devices in current use
- Nutrient runoff and the phosphorus "leakage" as a result
- Implementation system to assist storage management and reduction in phosphorus runoff as a result of out of season application and snowmelt

Current on-farm liquid manure application systems lack the ability and tools to prevent water run-off. This results in the manure's nutrients causing pollution and eutrophication that negatively affects the water table. Liquid waste is currently stored in large lagoons; however, these storage systems have very limited space and are being filled with animal manure year-round. Due to the restrictions on periods of application during the fall and winter as well as the runoff potential during snowmelt, farmers often must deal with storage and nutrient management issues. To solve this issue, AGIS has designed a setup to first separate liquid and solid waste using a gravity-based screen separator and roller, and then reclaim phosphorus through the production of struvite. This system will allow farmers to capture the nutrients from liquid manure and then return them to the crops when there is less chance of nutrient runoff. This will result in a great benefit to the crops and much more. The benefits of this proposal include:

- Reduction of Eutrophication in Rivers, Lakes, and Aquifers

- Increased crop nutrient absorption by applying phosphorus dense fertilizer at optimum growing times
- More reliable storage of fertilizer in the form of struvite crystals

2 Introduction and Background

To understand the problems caused by improper waste management, nutrient runoff, and eutrophication, there requires a basis of knowledge in animal agriculture farm manure distribution and application. The process of manure distribution can be split into a number of main components including Collection, Processing, Nutrients, Filtration, and Application. Each of these varies from farm to farm but the main methods and practices are fairly universal on large to moderate-sized farms. Nutrient runoff and subsequent eutrophication is a complex problem that has no one clear solution. The problem begins at the edges of farms but ends many kilometers away at local ponds, lakes, and aquifers.

2.1 Current Liquid Manure Collection Systems

Most of the manure that is applied to fields is in a liquid state as opposed to a solid compost state that smaller farms might take advantage of. Methods of collecting liquid manure are dramatically different from solid manure which is defined as 15% or greater solid content. The majority of Liquid manure (>5% solid content) comes from large scale dairy and pork farms where a liquid solution is used to flush out stalls [1]. This flushing process carries the manure slurry to large open lagoons or smaller closed systems through both gravity-assisted pipes or low suction pumps [1]. The purpose of these lagoons is both temporary storage before the slurry is pumped out and sprayed on cropland and pasture, and a sedimentation system for solids to separate out. The liquid/solid separation procedure can vary depending on the solid content of the waste, but common methods are chemical treatment, presses, sedimentation, screen separators, or centrifuges [12]. Depending on the type of manure and local environmental regulations, the danger of runoff and environmental contamination can be quite high. Guidelines for both collection and storage are in place to avoid this and require maintenance and upkeep to keep aquifers and local water tables safe. Often plant stripes and irrigation channels are used to control the direction and absorption of runoff [8].

2.1.1 Storage Capacity and Application of Manure Time Periods

There are several methods used in Liquid Manure Storage including Slush Bars, Concrete Silos, and Earthen Pits (Lagoons). The most common of these is the Lagoon. This is a simple system where manure is flushed into either a covered or uncovered large pit where the solid sediment can settle out and the liquid remainder can be easily pumped out and applied to fields and pastures [25]. Liquid Storage planning is an important part of the fertilization and animal agriculture farming business. It is important to determine when to spread manure to avoid overflow of storage but there are significant restrictions and dangers of spreading manure during the winter and runoff season [26]. Since animals create excrement year-round, weighing environmental impact against storage backup can be a difficult task (Table 1 & Table 2). Developing a system to allow for late fall and winter application of manure to apply some level of nutrients to the soil and increase storage capacity during the non-growing season while decreasing runoff potential would dramatically help farmers. Such a system would be ideal for Manitoba hog farmers in 2019 when due to a rainy fall season many were left with lagoons that were filled at max capacity already past the cutoff date for winter manure application [27].

Livestock	*Wet mass*†	*Total dry solid*
	-------------------- lb	--------------------
Feeder cattle	52.0	7.1
Dairy	78.0	10.7
Swine (100 lb hog)	88.4	8.1
Poultry		
Broiler	87.9	24.6
Hens	72.7	17.8
Turkey	55.0	12.3
Sheep	39.0	11.3
Horse	54.0	16.5

Table 1: Manure Production per 1,000 lb live animal weight per day [42]

REQUIRED MANURE STORAGE CAPACITY FOR A FREE STALL DAIRY OPERATION WITH A GIVEN NUMBER OF MILKING COWS

Number of Milking Cows	180 days		210 days		240 days	
	(litres)	(cubic feet)	(litres)	(cubic feet)	(litres)	(cubic feet)
40	918,000	32,400	1,071,000	37,800	1,224,000	43,200
50	1,121,000	39,600	1,307,000	46,200	1,494,000	52,800
60	1,350,000	47,700	1,575,000	55,600	1,800,000	63,600
70	1,566,000	55,300	1,827,000	64,500	2,088,000	73,700
80	1,796,000	63,400	2,095,000	74,000	2,394,000	84,600
90	1,998,000	70,600	2,331,000	82,300	2,664,000	94,100
100	2,228,000	78,700	2,599,000	91,800	2,970,000	104,900
120	2,673,000	94,400	3,119,000	110,200	3,564,000	125,900
150	3,321,000	117,300	3,875,000	136,900	4,428,000	156,400
200	4,428,000	156,400	5,166,000	182,500	5,904,000	208,500
300	6,615,000	233,600	7,718,000	272,600	8,820,000	311,500

Table 2: Required Manure Storage Capacity for a Free Stall Dairy Operation with a Given Number of Milking Cows [33]

2.2 Existing Animal Waste Processing Technologies

Farms are currently using technology and machinery to help them in the processing of their animal wastes. These procedures aim to improve the manure as a fertilizer, allowing for onsite usability, and minimizing the pollutant qualities. As mentioned in Current Liquid Manure Collection Systems, livestock farms will separate their solid and liquid manure using mechanical belts and screws to obtain slurry and liquid manure [15]. This liquid manure is beneficial for farms as it can be easily pumped into spreading equipment and applied to their land [3]. Additionally, this liquid manure often goes through the process of nutrient removal in hopes of being able to reuse the extracted nutrients for fertilization. One existing method of this is vermifiltration, where liquid manure is run through a combination of screens, wood chips, bark, peat, straw, and earthworms to create a less harmful version of the waste. Furthermore, a film of organic matter and nutrients will build up on the screens, ready for collection [11]. Through the use of vermifiltration, not only are farms given access to their own personal supply of nutrients, but they end up with a much safer form of liquid waste that presents less of a threat to the surrounding environment.

2.3 Filtration Systems of Water Table

Pollution to the water table is a major contributor to the disruption in water ecosystems. Farms are especially at fault for this pollution due to their mismanagement in animal waste. A simple way to fix this would be to create a filtration system that would filter the harmful nutrients from the animal waste out of the water as it seeps through the soil and into the groundwater, however it seems to be quite impossible. Once water enters the ground, there is no effective process to clean out the harmful substances that it may be carrying. The only current "method" of water table filtration is the use of coarse soil containing sand and gravel to collect and trap the nutrients and harmful bacteria from continuing through the water cycle (Figure 1) [7]. Instead of focusing on filtering the water table, farms have been trying to reduce the amount of liquid waste that enters the groundwater. This includes creating buffers; lining the edges of the farm, as well creating strips of shrubs to guide/absorb runoff [6]. Due to the challenge of filtering the liquid waste within the water table, farms have tried to tackle the easier challenge of reducing the total amount of waste that enters the groundwater, and while it is theoretically less efficient, it is still the next best solution.

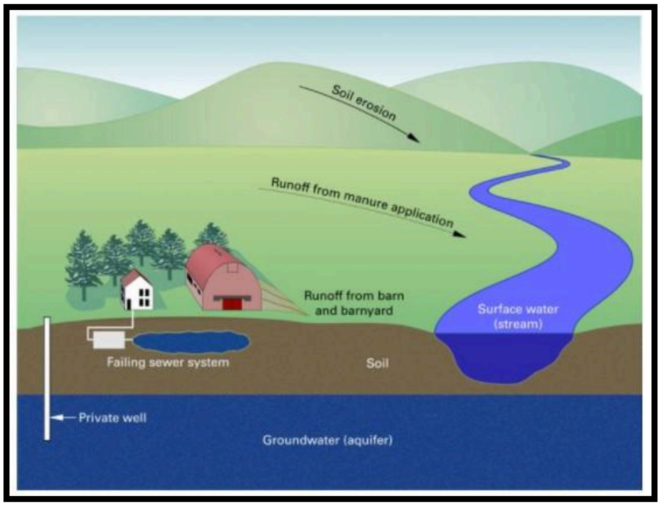


Figure 1: Routes and Topological Determinants of Runoff [7]

2.3.1 Nutrients in Animal Waste

The nutrients contained in animal waste is dependent on many factors, which include, the species of farm animal, diet, type of bedding, water content, and storage method. In general, the core nutrients in manure are nitrogen, phosphorus, and potassium (Table 3 & Table 4). In addition, to these three elements, the organic fiber, traces of calcium, magnesium, and sulfur will improve the health of the soil to which the manure is spread upon. Nitrogen is vital to all plants and is a key ingredient in a successful crop yield. "Nitrogen in manure is found in the organic and inorganic forms" [34]. The primary inorganic nitrogen compound is NH_4-N. The inorganic form is prone to ammonia volitation, which is when the nitrogen becomes separated from the NH_4 molecule. Also, the organic nitrogen needs to be mineralized before it can be used by the plants on that field, therefore, not all the nitrogen is available after applying the manure. Phosphorus in the form of phosphate is needed for all forms of life. More importantly, phosphorus is needed in high quantities for crop fields and a lack of available phosphorus can significantly reduce the yield of said field. Similar to nitrogen, phosphorus is present in both organic and inorganic forms that have similar properties to its nitrogen counterpart. Additionally, solid animal waste will have a higher nutrient content than liquid waste because of the dilution process. Often manure will not contain the required amount of certain nutrients for a crop or on the flip side the waste may contain too much of a particular chemical, rendering the manure either ineffective or inefficient. Additionally, commercial nutrients may be required to balance the nutrient content to achieve optimal soil conditions [43].

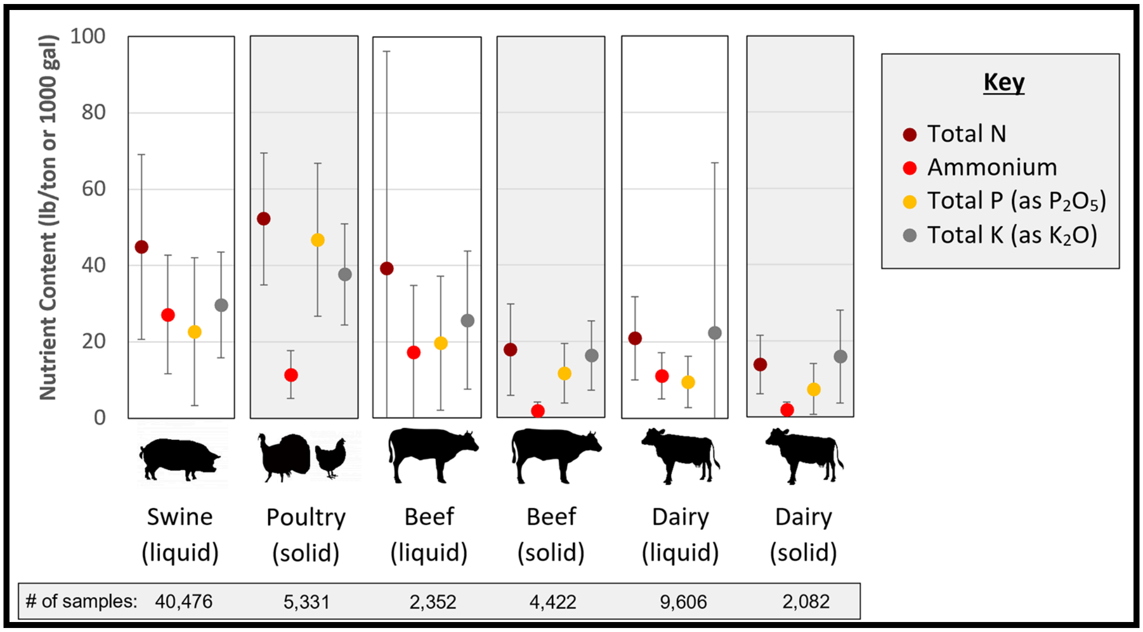


Table 3: Range of Manure Characteristics from Livestock Species [41]

BC Anaerobic Digestion Benchmark Study															
Feedstock Characteristics															
Feedstock	**TS Range** (%/mass)		**VS Range** *(%TS)*		**N - Range** *(%TS)*		**P-Range** *(%TS)*		**K-Range** *(%TS)*		**C:N Ratio Range**		**Biogas Prod Range** *(m3/tonne)*		**References**
Dairy Manure	6	11	68	85	2.6	6.7	0.5	3.3	5.5	10	10:1	17:1	20	26	
Average	***8.5***		***76.5***		***4.65***		***1.9***		***7.75***		***14:1***		***23***		1, 10
Beef Cattle Manure - in barn	8	12	80	85	2.2	6.8	1	1.5	3	7.5	7:1	12.5:1	19	46	
Average	***10***		***82.5***		4.5		1.25		5.25		9.8:1		***32.5***		2,3
Beef Cattle Manure - pasture	25	35	60	85	1.1	3.4	1	1.5	3	7.5	14:1	25:1	80	112	
Average	***30***		***72.5***		***2.25***		***1.25***		***5.25***		***19.5:1***		***96***		1, 10
Hog Manure	2.5	9.7	60	85	6	18	2	10	3	7.5	9:1	16:1			
Average	***6.1***		***72.5***		***12***		***6***		***5.25***		***13:1***		***25***		1, 4
Poultry (Layer) Manure	15	65	70	80									48	208	
Average	***40***		***75***		***4***		***3***		***2***		***7:1***		***128***		1, 5, 6
Poultry (Broiler) Manure			70	80											
Average	***75***		***75***		***4.6***		***1.5***		***1.5***		***9:1***		***93.8***		1, 6, 7
Horse Manure	28		75		2.1		1		1.8		25:1	35:1			
Average	***28***		***75***		***2.1***		***1***		***1.8***		***30:1***		***63***		1, 8, 9, 10
Fats Oils Greases (FOG)	2	30	70	99	0.1	3.6	0.1	0.6	0.1	0.5	9:1	15:1	150	300	
Average	***16***		***84.5***		***1.85***		***0.35***		***0.3***		***12:1***		***225***		1, 10
Dissolved Air Flotation (DAF) Material	5	40	85	98	3	9	1	3	0.06	0.2			43	340	
Average	***22.5***		***91.5***		***6***		***2***		***0.13***		***N/A***		***191.5***		1, 10
Source Separated Organics (SSO)	9	37	75	98	0.6	5	0.3	1.5	0.3	1.2	18:1		91	160	
Average	***23***		***86.5***		***2.8***		***0.9***		***0.75***		***18:1***		***125.5***		1,10
Bakery Waste					3.5	4							265	344	
Average	***88***		***97***		***3.75***		***1.5***		-		***N/A***		***304.5***		1, 10, 11
Brewery Waste	3	21	66	95	4	5	1.5		1.2		9:1	10:1	13.2	92.4	
Average	***12***		***80.5***		***4.5***		***1.5***		***1.2***		***9.5:1***		***52.8***		1, 10
Septage	1	13			0.8	5.8	0.58	1.8							
Average	***7***		***79***		***3.3***		***1.19***		-		***11:1***		***13***		12, 13
Saughterhouse Waste (Viscera)	14	15	82		2.6		1		0.7		19:1		56.5	60.5	
Average	***14.5***		***82***		***2.6***		***1***		***0.7***		***19:1***		***58.5***		1, 10
Potato Culls	12	15	90		5	13	0.9		6.4		3:1	9:1	55.5	67.7	
Average	***13.5***		***90***		***9***		***0.9***		***6.4***		***6:1***		***61.6***		1, 10
Fescue Straw											20:1	22:1			
Average	***86***		***19***		***3***		***0.3***		***2***		***21:1***		***307***		10, 14, 15, 16

Table 4: Range of Nutrient values in Livestock Manure [34]

2.4 Nutrient Runoff and Water Pollution

Nutrient runoff from edges of farms poses a significant risk to lakes, rivers, and aquifers and is one of the leading issues in water management. Phosphorus leaching from soil following fertilizer application is one of the leading causes of eutrophication and algal blooms [21]. Especially in "...SE Manitoba and SW Alberta..." where there is a high level of animal agriculture P runoff is high [21]. Combined with the fact that these areas experience a high level of snowfall and snowmelt greatly contributes to nutrient loss from fields. There are a couple of methods to limit the loss of nutrients from fields including conservative tillage, plant buffers, and holding ponds. These methods are highly subject to the environment through and therefore do not fit every farm's needs [22]. These methods are referred to as BMPs (Best Management Practices) and although they often work well in warmer climates, they often fail to have the most efficient outcome in colder climates [21].

2.4.1 Eutrophication

Eutrophication is the process that encompasses the negative effects substantial algae blooms have on an ecosystem. These algae blooms overload the biocapacity of lakes, rivers, and streams causing oxygen dead zones and substantial deteriorative effects to local flora and fauna. Not all causes of Eutrophication are completely understood but it has been established that "excessive nutrient loading into [the] surface water system is considered to be one of the major factors" in its development [23]. The real question that research is trying to solve is how to stop, slow, or reduce eutrophication. "Excessive nutrients(s)" can refer to a lot of things, but the major influencing factor is inorganic phosphorus and nitrogen runoff. According to the EPA the largest source of phosphorus and nitrogen runoff is agriculture and specifically "excessive fertilizer" applied to fields and pastures [24]. Phosphorus is the limiting factor in large scale algae bloom development and is the most important factor in stopping or slowing it down (Figure 2) [23].

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+ \xrightarrow{\text{Energy + microelement}} C_{106}H_{263}O_{110}N_{16}P\,(\text{boiplasm of algae} + 138O_2)$$

Figure 2: Chemical Formula for Development of Algae and the Nutrients Involved Overproduction [23]

3 Development of the Project

3.1 Liquid-Solid Separation

The separation of liquid and solid manure is a crucial component of any farm's waste management system. Manure in its initial form is not ideal in terms of handling, however after separation, both products may be utilized for different situations. The machine used in the separation process is very important, as it will determine the efficiency at which the waste is separated, and the solid content in the liquid after separation. The more efficient the model, the lower the solid content in the liquid will be. Our developed separator ensures the minimal amount of solid concentration in the processed liquid manure, all while working at max efficiency.

3.1.1 Model

The developed design of the liquid-solid manure separator consists of two highly effective systems that will maximize the separation process. The first major component to this design is a vibrating screen separator, that functions at an angle for optimal efficiency. The physics behind vibrating screen separators follows simple mathematical and chemical laws. Rapid vibrations from the screen cause the solids to accumulate, while the liquid seeps through. The steep inclined angle helps to move the manure along the screen using gravity to assist resulting in minimal power used in the mechanical systems. At the bottom of the vibrating screen, a rolling press consists of a large and small roller. This rolling press functions as an additional separator, separating any remaining liquid in the manure by rolling the manure through its high-pressure zone. Once the manure has passed through the rolling press, it is deposited on a collection surface. The separated liquid is collected underneath, where it awaits the next process (Figure 3).

3.1.2 Economics

This liquid-solid manure separator has the throughput capacity of 100 to 600 gallons of liquid manure every minute, and costs roughly $1000 to $5000. This price excludes the price of any pumps, sumps, channels, and operating costs [28]. The addition of an electrical generator may assist in the operation of the separator. During winter, cold temperatures may cause the machine's operation to halt, therefore the addition of a heat generator may be necessary [29].

Furthermore, these machines can second as manure storage, increasing the total lagoon’s storage size. This in turn will save money on costs to store manure. This reduction in mass/volume clears up more space within the lagoon storage systems, therefore preventing manure from overflowing the lagoon. This results in more money saved, as the amount of waste manure would be reduced significantly. Also, the transportation of dry manure is much simpler in terms of cost and efficiency when compared to transporting wet manure.

3.1.3 Maximization of Nutrient Separation

Phosphorus is a primary cause in Lake Winnipeg's eutrophication problem, and the liquid-solid screen separator provides a phenomenal solution to this problem. Due to the insoluble nature of phosphorus, it is unable to go through a vibrating screen with the water, therefore it sticks to the dry manure [30]. This separation process promotes the recycling and reusing of phosphorus, creating an efficient system to maximize usage of the nutrient. However, other nutrients that contribute to eutrophication such as nitrogen and potassium are soluble, making it much more difficult to separate from the liquid portion of the manure. Apart from this, being able to remove one of the most primary causes of eutrication from the liquid manure, phosphorus, will produce great results for the water quality.

3.1.4 Removal of Fiber Content

Removing the fiber content from manure is very important for the standard health quality of dairy farms. Fibers from the manure are used in cow bedding, as they absorb liquids and provide comfortable cushioning, maintaining clean stalls for the cows. Lastly, extracting fibers from the manure benefits the machines handling waste, as the process of removing fiber protects any foreign materials from possibly harming the other machines [31].

3.1.5 Design Specifications

To maximize and optimize the solid separation in the design, an angled screen and roller component where implemented. The most important factor in optimizing the solid separation in this design is the screen mesh size [32]. To provide the lowest solid particle content to the struvite formation tank, as well as retain the slurry content, a mesh size of 100-120 (150µm-125µm) should be used. The "Maximizer" is a model similar to the one we have constructed and allows for the highest flow rate through the design. Finally, this design and screen size allows for a greater phosphorus and solid fiber separation (Figure 4).

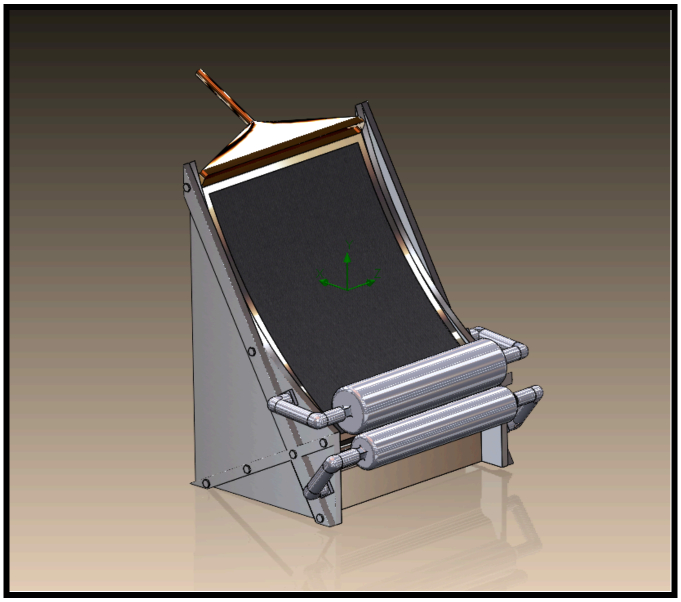


Figure 3: 3-D Solidworks Model of Screen and Rollers

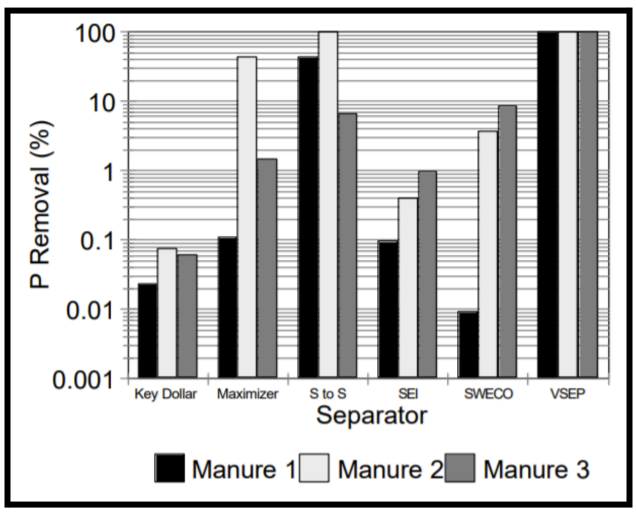


Figure 4: Phosphorus removal from separator [32]

3.2 Phosphorus Removal Mechanism

Wastewater, sewage, and other forms of aqueous solutions of excrement all share a percentage concentration of phosphorus and other nutrient elements and compounds. These nutrients contained in the wastewater can be extracted using various methods and reused as a form of fertilizer. Currently plentiful amounts of wastewater is making its way into lakes and rivers causing eutrophication and exhausting any potential means of creating fertilizer. The removal of phosphorus is crucial in the process of improving the states of our lakes suffering from eutrophication caused by pollutants. In these next few paragraphs the methods of phosphorus removal, the application of struvite as a fertilizer, the methods of struvite extraction, and the optimization of struvite formation are discussed and analyzed as part of the research in determining the optimal design path to efficiently extract the nutrients from the wastewater, remove the formed struvite crystals from the system, and utilize the struvite as an on-farm premium fertilizer. All while being affordable and profitable for cattle and crop farmers.

3.2.1 Phosphorus Removal Methods

Current phosphorous methods are most applicable in removing the chemical from waste waters. The current phosphorus removal methods consist of two main categories: chemical and biological. The first, chemical removal methods typically involve "precipitating… phosphorus with an iron or aluminum salt" [35]. This requires large tanks of wastewater for the reaction to occur. Benefits of chemical removal are it limits the odors and scum produced [35]. This is similar to the approach of this team's solution, but with one key difference. That difference is that Magnesium chloride will be the reacting ingredient in the phosphorus removal process. The magnesium compound will react with the phosphorus and other chemicals to form struvite (see section 3.2.3). Second, biological removal uses phosphorus-accumulating organisms. This method "is considered to be a cost effective and environmentally sustainable alternative to chemical treatment" [44]. The phosphorus-accumulating organisms consume the phosphorus, therefore removing the chemical from the wastewater. The key to the biological removal method is the acquiring of the phosphorus-accumulating organisms. The most common technique is to use an "anaerobic-aerobic sequence" of water tanks [35].

3.2.2 Struvite as a Fertilizer

Struvite has been shown to be a sustainable and effective alternative to conventional fertilisers by many studies. As a slow-release fertiliser struvite reduces phosphorus losses to runoff during rainfall because of its low solubility. Whereas conventional fertilisers are readily soluble, and rainfall after application causes large amounts of phosphorus lost to runoff – causing eutrophication. [18] Struvite-based fertilizers have a lower danger of burning plant roots with a low SI (salt index), additionally the "content of heavy metal ions" is significantly lower "than commercial fertilizers" [19] Another benefit is the renewability of struvite, compared to conventional fertilizers coming from mined phosphorus, which is a limited resource that takes approximately 10 to 15 million years to form naturally. [20] Considering these factors, it can be concluded that it is crucial to find an alternative to conventional fertilisers. Struvite has proven to be a viable option by lowering pollution to the water system, and being readily available for recapture from farm wastewater.

3.2.3 Methods of Struvite Formation

Struvite is a mineral formed from the presence of magnesium, ammonia, and phosphate in a system. The chemical formula: $Mg_2^+ + NH_4 + PO_4^{-3} + 6H_2O \rightarrow NH_4MgPO_4 \bullet 6H_2O\ (s)$

displays the process in which struvite is formed, and the mole to mole ratio 1:1:1 at which the ideal quantities of elements are provided for the formation of struvite [38]. The formation of struvite is normally seen and recognized as kidney or bladder stones, however, in this report the focus is diverted to struvite formations in wastewater. Wastewater contains sufficient concentrations of phosphates and ammonia as well as an adequate ionic speciation, temperature, and pH involved in the formation of struvite (Figure 5) [39]. The only missing piece is the magnesium which can be added to the wastewater in precise quantities to meet the requirements for struvite formation. In wastewater plants the suggestive signs that struvite will form in the system is a high pH, a high conductivity, low temperatures, and high concentrations of ammonia, phosphate, and magnesium. Our project design transports wastewater in part through a filtration system to individual tanks. Precise quantities of magnesium are then added to the wastewater to induce struvite formation, meeting all the ideal conditions; 1:1:1 mole to mole ratio, pH, temperature etc. The struvite is then collected to recycle nutrients from animal waste using the struvite as a form of fertilizer.

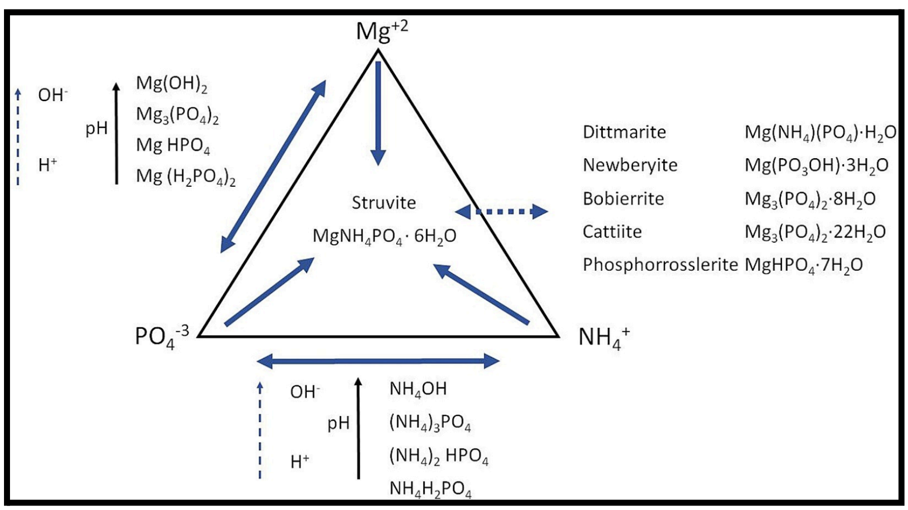


Figure 5 : Building Blocks of Struvite Formation and Optimization Relationships [39]

3.2.3.1 Air Agitation Crystallizer

<u>Pros:</u>

This type of crystallizer mixes efficiently achieving a phosphorus removal rate of 81 to 86% in known studies. Gases such as carbon dioxide and ammonia are vented out achieving a higher pH value in the overall solution.

Cons:

The struvite crystals are unable to grow large as a result of a lack of time and volume in the crystallization process. This system also requires frequent maintenance, replacing the padding or membranes. Lastly, if the machine were to break down for any reason the restart process is difficult.

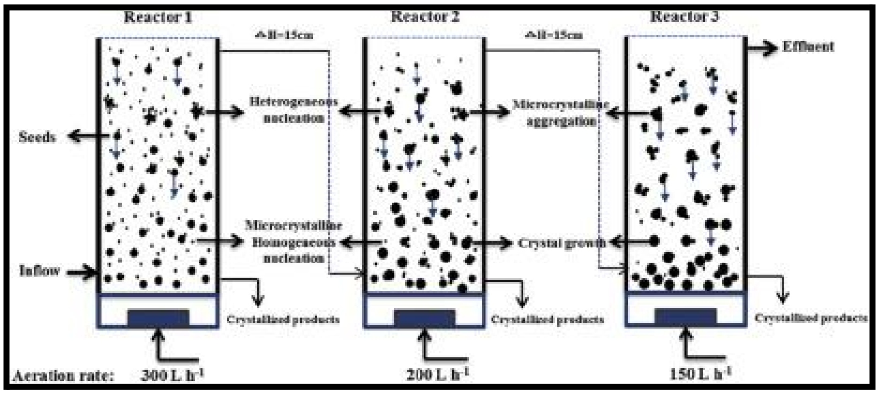


Figure 6: Air Agitation Crystallizer System [45]

3.2.3.2 Water Agitation Crystallizer

Pros:

This system is designed in a way where even the finer struvite particles stay are not filtered out of the machine, because of this the system can remove 92% of the phosphate and achieve a struvite crystal with a purity of up to 99% [37].

Cons:

It is recommended to use seed crystals to achieve optimal results.

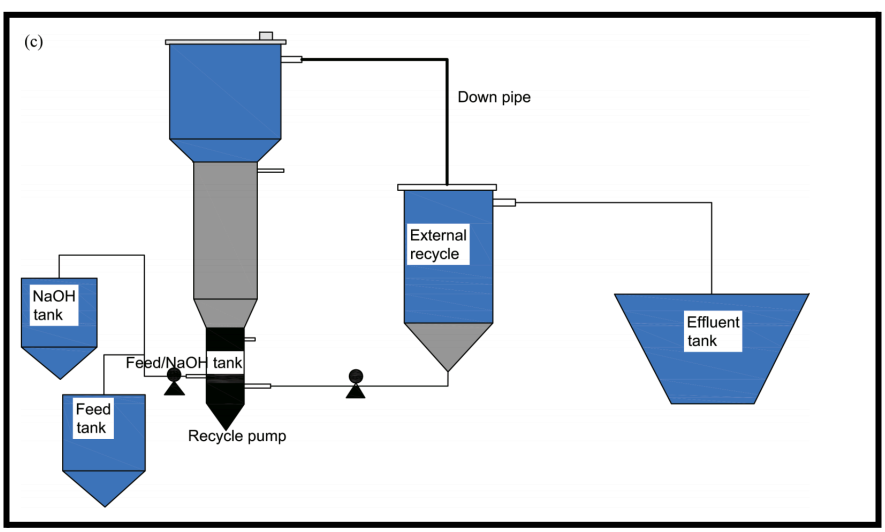


Figure 7: Water Agitation Crystalizer System [37]

3.2.3.3 Mechanical Agitation Crystallizer

Pros:

This design utilizes an impeller mixing method for struvite crystallization. This method is easy to operate and can achieve a struvite crystal purity of up to 99%. New modern designs show that the use of a mixed product removal crystallizer, “MSMPR could increase the size of crystals, improve the crystallization rate of the struvite, and enhance the phosphorus recovery rate” [37].

Cons:

This energy required to run this machine exceeds that of any of the other crystallizers. “Mechanical Agitation Crystallizers create uneven sizes of struvite crystals; however, current research shows that a mixed product removal crystallizer can solve the problem of unevenly sized crystals” [37].

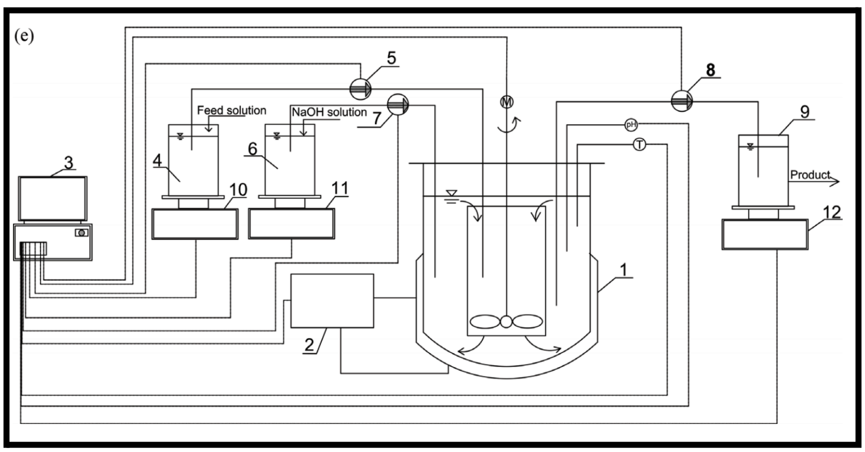


Figure 8: Mechanical Agitation Crystallizer System [37]

3.2.4 Optimization of Struvite Formation

An essential factor in the struvite formation process is encouraging large and uniform crystal growth that will improve recovery efficiency, and fertilizer quality. A larger crystal helps with separation, as a larger mass influences its settleability helping prevent the struvite from recirculating to the output. Further, larger particle size increases collisions among the reactants which results in faster reaction times. The larger size also reduces solubility of the struvite – retaining more of the phosphorus, and nitrogen from recirculation. Lastly, achieving the proper granular structure is beneficial for transportation, and eliminates further processing for use in farm spreading equipment. Therefore, it is crucial to optimize the formation process of struvite as proper growth, structure, and size contributes to phosphorus recovery, and a superior product for fertilization.

The following will address the optimal crystalline structure of struvite, how this structure affects larger crystal growth, and what conditions need to be considered to best achieve these results.

Factors discussed are the molar ratios of reactants, pH level, aeration effects, and time required for optimal struvite formation. The main source of this data is from the article: Engineering of struvite crystals by regulating supersaturation – Correlation with phosphorus recovery, crystal morphology and process efficiency [36].

The denser crystalline structures found in zone (1) are more optimal since they produce consistently larger particle sizes, improving settleability and aggregation properties (Figure 9). Structures in zone 2 and 3 achieved high phosphorus recovery but lacked in density, with an increased surface area resulting in higher solubility causing increased difficulty in separation [36].

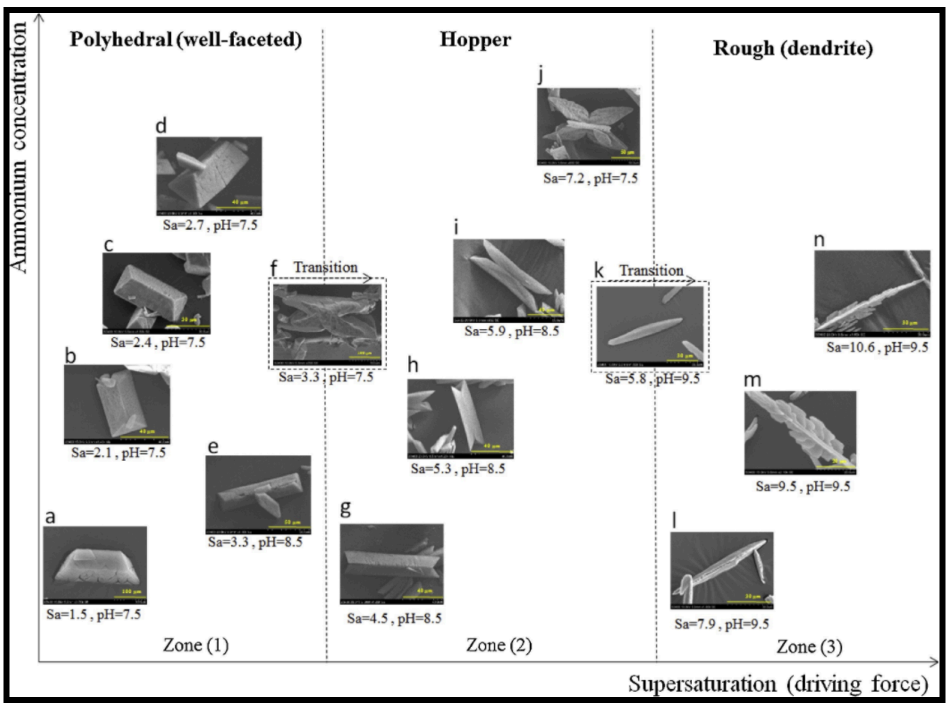


Figure 9: Struvite Morphology plotted by Ammonium concentration vs Supersaturation [36]

Molar ratios that maximized phosphorus recovery occur with greater than six parts of nitrogen to phosphorus, this was strongest at pH of 7.5, where higher pH levels were less affected by the molar ratios (Figure 10).

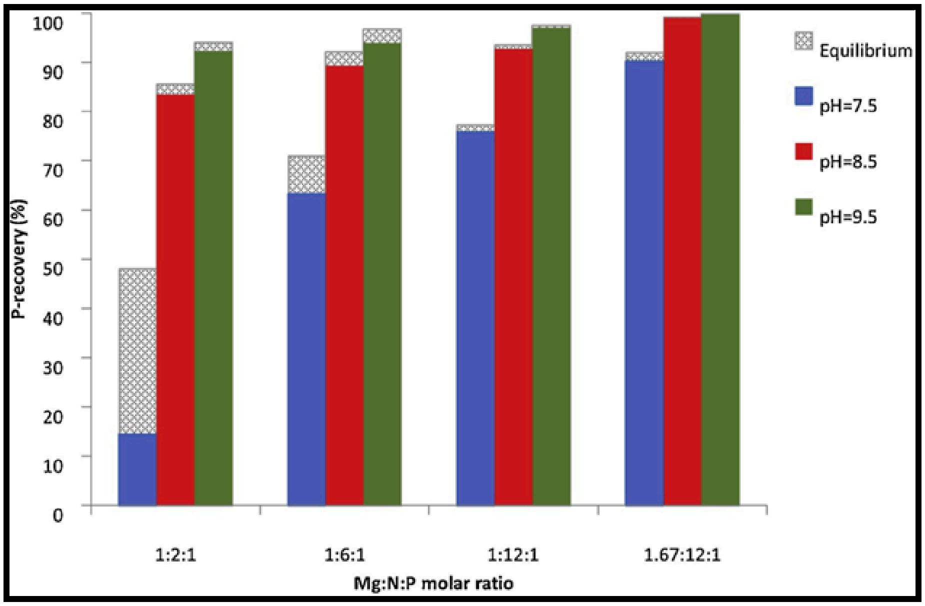


Figure 10: Percent of Phosphorus Recovery from differing Molar Ratios of Mg:N:P & pH levels [36]

However, lesser ratios with more than two parts nitrogen are still shown to be effective. Thus, confirming that struvite formation is plausible for varying compositions of farm waste. Although higher amounts of nitrogen increase phosphorus recovery, it is not necessary for the desirable crystal structure. The highest volume of large crystals was formed with a lower pH due to the lower negative surface charge on the crystals causing less repulsive forces between each other, resulting in stronger and more uniform bonds between the ions (Figure 11).

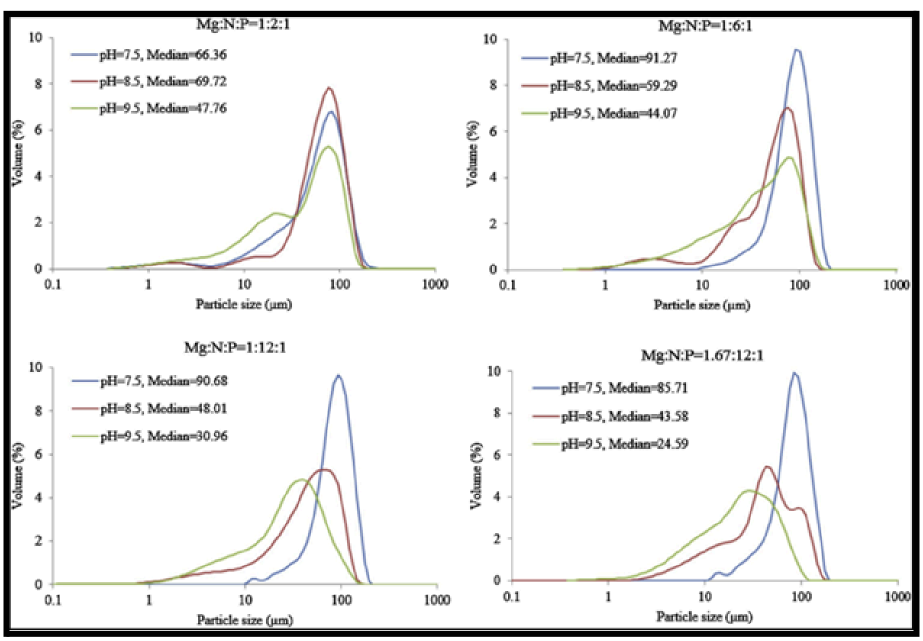


Figure 11: Phosphorus Recovered vs Particle Size from differing Molar Ratios & pH levels [36]

Implementation of Aeration is the primary method of increasing pH without addition of chemicals. Gentle aeration in the form of stirring showed the best results, causing enough collisions of struvite particles without losing struvite to the output from excess turbulence.

The previous factors all influence the reaction rate, and it was observed through the results that to achieve the desired larger size of crystals a minimum of 60 minutes should occur. With lower pH levels being optimal, whereas the molar ratios are less important than maintaining a consistent level of concentration throughout the reaction.

3.2.5 Model and Iterations

Throughout the design process of the Struvite Reactor, many ideas and models have been created. Although countless iterations have existed, they can be reduced into more general stages that better exemplify the thought process.

The first stage of the design process begins with hand drawn sketches. These sketches provide the framework and basic ideas that the rest of the design will be built upon.

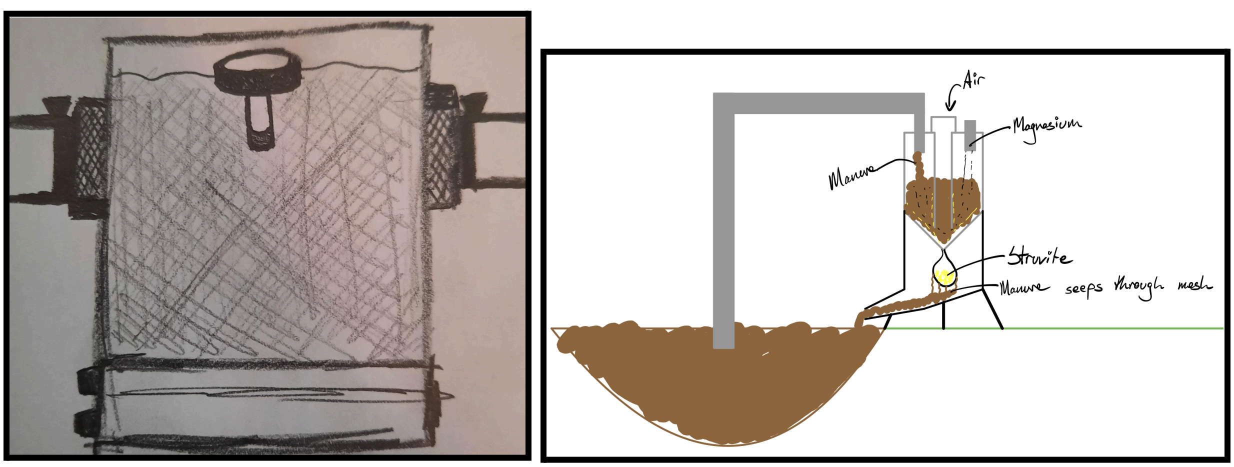


Figure 12 & 13: Original hand-drawn sketches of the two Struvite Reactor variations

The next stage of the design process is when we first think about true functionality and of what may limit our product. This stage consists of the main parts of the model, with a focus on a realistic model. Not much brainstorming has occurred at this point in the process, and core issues may exist within the design. The final product may look vastly different.

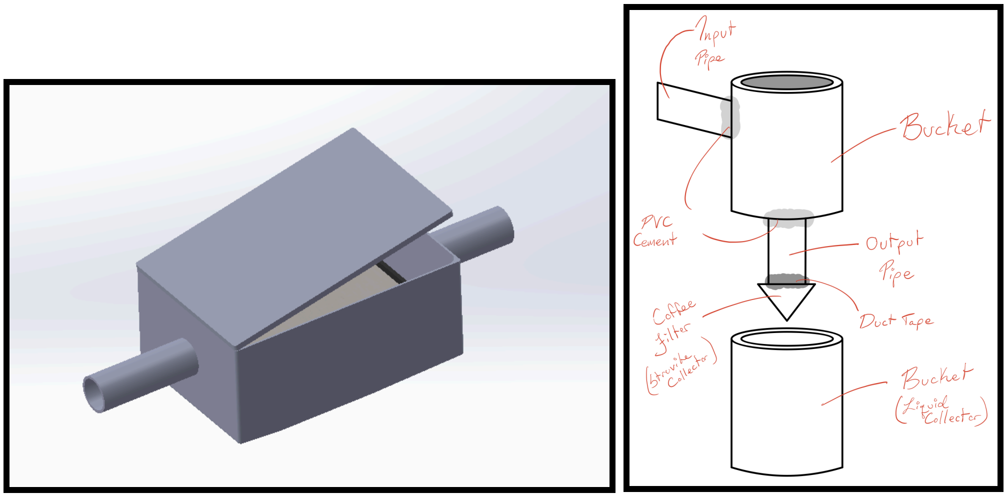


Figure 14 & 15: Both variations of the second stage of the Struvite Reactor design

The third stage of the design process is the last stage that involves major changes in the actual design of the system. From this point on, the bulk of the design will not change. The key focus in this stage is the functionality of the product, as well as ridding the design of flaws.

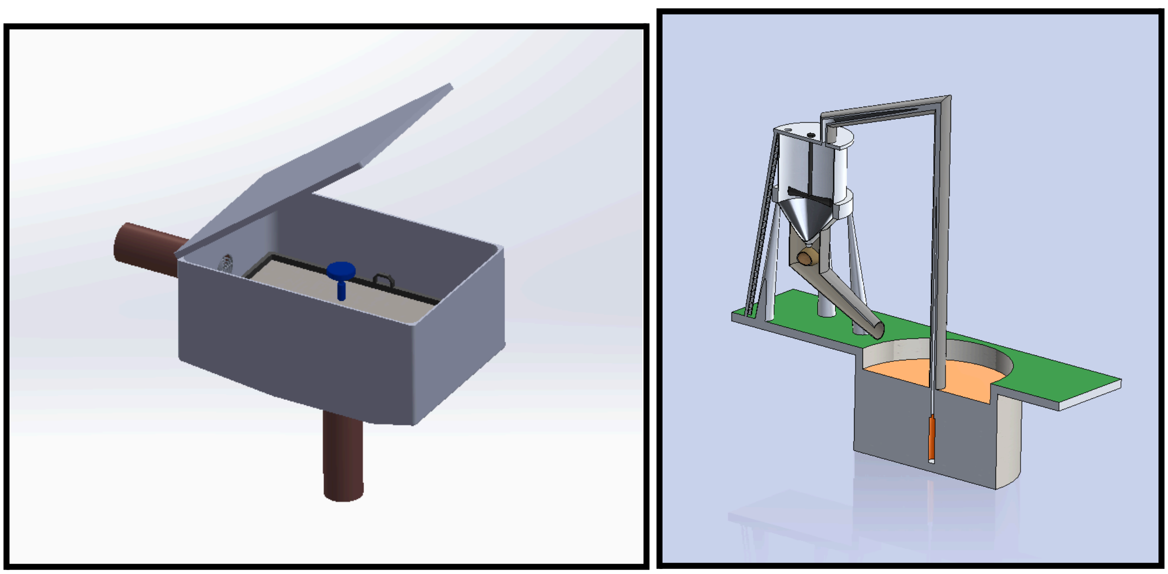


Figure 16 & 17: The third stage of two Struvite Reactor variations

The fourth and final stage of the process consists of refining the design so that it is finalized. In this case, this stage also required the choice between two potential designs, or a combination of both. The final product can be seen in the section below.

3.2.6 Design Specifications

For the purposes of this project, we designed and modelled a Struvite Reactor. This reactor acts as the core of our process and is the setting for the main chemical reaction of our system. In essence, the Struvite Reactor is a sizable reaction tank with a horizontal input pipe and a vertical output pipe. Liquid waste, which is rich in phosphorus, is pumped from an on-farm wastewater lagoon into the reactor via the input pipe. Once inside, a magnesium distributor slowly releases magnesium chloride into the wastewater. It does so by the inclusion of a slow-release magnesium chloride tablet, in which highly soluble magnesium chloride is trapped within a net of a low solubility solid. Over time, magnesium chloride will slowly find its way through the net and into the reaction tank. Due to the agreeable pH level and turbulence of the liquid, struvite crystals are rapidly formed as magnesium ions react with phosphorus ions. The struvite crystals are then caught by the nylon mesh, which allows the liquid to pass through into the output pipe. This pipe leads back into the wastewater lagoon, thus creating a constant cycle and flow.

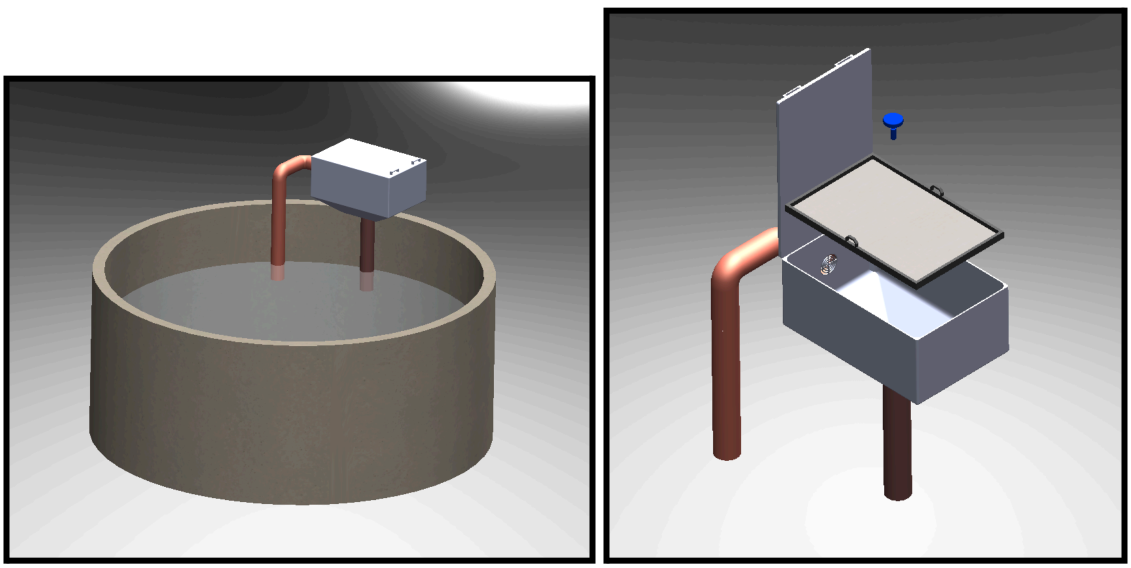


Figure 18 & 19: Two views of the final design of the Struvite Reactor

As shown above, the Struvite Reactor can be easily and cheaply implemented into a pre-existing lagoon. Additionally, with a change in piping materials (from metal to PVC), the consistent nature of the Struvite Reactor's flow allows for use in even the coldest of climates. Overall, the Struvite Reactor paired with a device that can separate animal waste into its liquid and solid states is an elegant and effective solution to the issue of runoff on cattle farms.

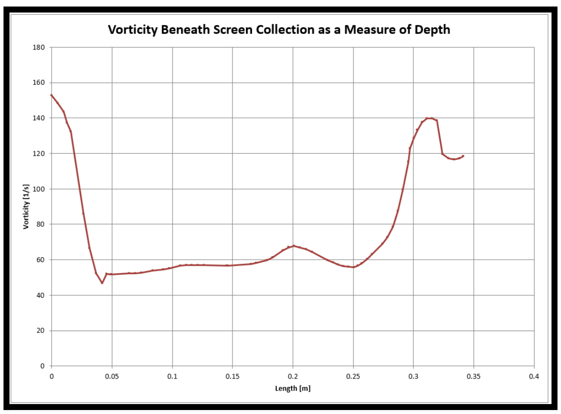
4 Experiment and Testing

4.1 Inclined Screen Separator

The model shown is the base standardized model for the Solid-Liquid Separations System developed specifically for AGIS and the Struvite Reactor System.

4.1.2 Solidworks Modeling and Liquid Flow Simulation

Below are two simulations showing the models ability to handle a constant flow of liquid. The measurements are given relative to the inclined screen and represent the pressure along that screen and the vorticity of molecules once passing into the interior of the separation system.



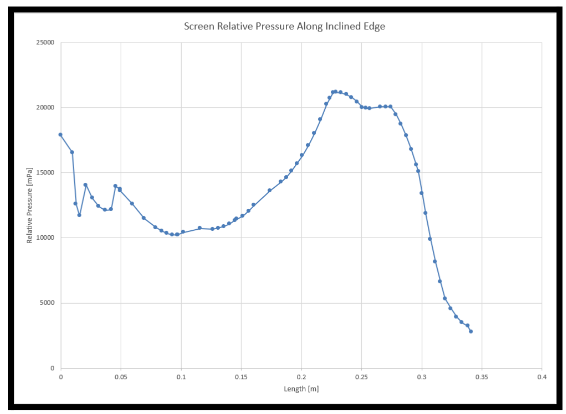
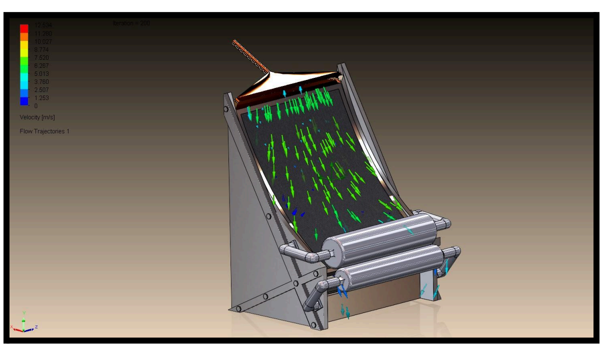


Figure 20: Vorticity Beneath Screen Collection as a Measure of Depth (left)
Figure 21: Screen Relative Pressure Along Inclined Edge (right)



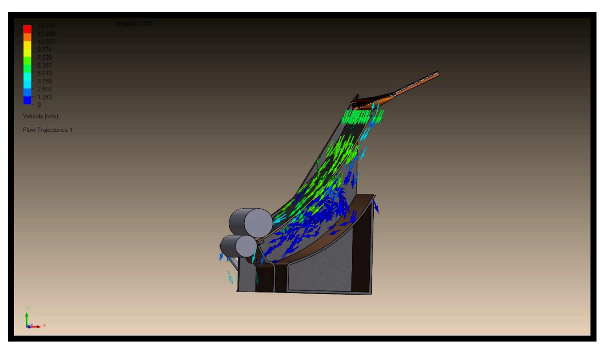


Figure 22 & 23: Solidworks Models of Exterior and Interior Flow Simulation

Here is a comprehensive model of both the exterior and interior flow simulation of liquid within and around the model components.

4.2 Struvite Reactor Prototype

To produce our own struvite, we created a scaled-down prototype of our struvite reactor. This conceptual design is composed of two buckets, a pump, a tube, and a filter. To represent the liquid manure, we used the combination of plant fertilizer and magnesium chloride. The plant fertilizer contained high contents of phosphorus, nitrogen, and ammonia, which react with magnesium chloride to produce struvite. Figure 24 represents the initial reaction of the fertilizer and magnesium chloride, and Figure 25 showcases the reaction after one day.

Figure 24 & 25: Fertilizer and Magnesium Reaction t = 0 hr, and t = 24 hr

5 Results and Conclusion

5.1 Struvite Production

After 24 hours of constant flow, the amount of struvite produced is shown here (Figure 26).

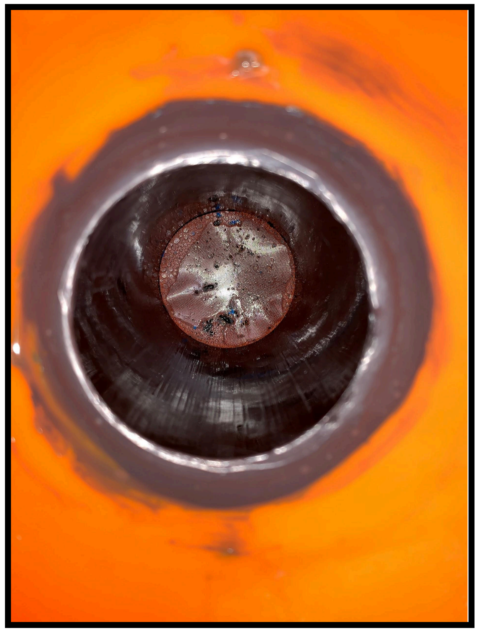


Figure 26: Struvite Produced

While this production may seem low, given our circumstances of limited materials and a budget, it was predicted. We were limited to the use of 1 kg plant fertilizer, and 250 mL of magnesium chloride, therefore the amount of struvite possible to produce was quite low.

5.2 Struvite Reactor Prototype Conclusion

Ultimately, while our prototype did not perform to the levels of an industrial sized reactor we hope to implement on farms, it proves our concept is possible and effective. This model differs from our finalized 3-D modelled prototype in the amount of turbulence created due to the water flow, and the dimensions of the mesh filter. This model shown in the previous figures shows what is possible with an inefficient pump, and 170µm mesh. Improving both of these features (as we have in our finalized model) will improve the struvite production by a gargantuan amount. Furthermore, the sheer change in scale alone showcases the potential of our reactor. Being able to produce some form of struvite on such a small scale only proves the product will increase as the model is sized to process on farms. This experiment demonstrates and confirms our theory related to struvite production and justifies how it would be a beneficial implementation to any farms waste management.

6 Future Work

6.1 Additional Struvite Reactor Design Challenges

While the design achieves its primary purpose, there are still many improvements that would benefit overall ease of use, and long-term sustainability. The optimal goal is a system that runs with minimal input of chemicals, is universally effective with all compositions of farm wastewater, requires minimal additional work for maintenance and collection, and is able to be implemented for large scale operations. The next steps in development would focus on the three following challenges:

1. Determine a sustainable source of magnesium for the reaction of struvite.

A major obstacle for sustainability of the system is the continuous need for the chemical magnesium. Currently research towards methods for supplying magnesium are limited, although one promising study shows seawater as a possible source [40]. However, this is limited to operations located near saltwater sources. Additional research is needed to determine a supply that is both sustainable and cost effective.

2. Automation of the system, reducing the need for manual maintenance and struvite collection.

The need to manually input magnesium and collect struvite routinely from the system may reduce interest in the design as it becomes more work for farmers. It is important to look at possible methods that will increase the time intervals between struvite collection and magnesium restocking to limit additional work. Further testing would be the first step in analysis to determine maintenance requirements, best methods for struvite removal and functions that can be automated.

3. Adaptation of design to accommodate varying compositions of farm waste and viability for large scale operations.

To increase adoption of this design it must become a viable solution for varying conditions. Optimizing the system to accommodate many types of use will require real world testing to analyze the key factors that influence struvite formations, and to identify unforeseen conditions that hinder efficiencies. Once all these factors are understood updates to design can then be implemented.

In order to pursue solutions to these challenges it is important to develop a fully working reactor that can be used in a real-world setting. This could then be used as a primary source of data to identify the key factors which reduce efficiencies and where to best focus resources in research and development.

6.2 Conclusion

Overall, the greatest limiting factor for the development of this system was the technical resources and funds available. To further develop this work and its accompanying systems a monetary investment would be necessary for testing prototypes, funding research, analytical testing, and applying what is discovered to optimize the design. Another consideration to increase effectiveness and usability of this system would be to explore ways to integrate the separation and precipitation process. Implementing a method of liquid separation and immediate struvite formation would not only cut down long term costs but would also create a more marketable product and efficient system. Currently much of the future development of the liquid solid separation lays in other private sector ventures but the addition of research into struvite formation, recovery, and storage is a growing and incredibly useful industry. In conclusion, gaining additional investments to fully develop a prototype for real world testing would enable the technological advancements that would allow for this system and its components to not only change the fertilizer market but also create a significant environmental impact for conservation of national ecosystems.

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8 Appendix

8.1 Economic and Environmental: Cost Benefit Analysis

Economic

Costs		
Item	**Quantity**	**Price**
Vibrating Screen Separator	1	$5000
Rolling Press	1	$5000
Struvite Reactor	1	$800
Magnesium source ($MgCl_2$)	-	$111/ton
Magnesium source ($MgSO_4$)	-	$420/ton
Magnesium source (MgO)	-	$544/ton
Operating costs	-	-

Benefits	
Item	**Price**
Struvite	+$1500/ton
Saves money on reduced waste storage overflow	

**Prices shown are considered more expensive options*

Environmental

Costs
Carbon footprint of production of machines
Carbon footprint of transportation
Carbon footprint of operation power

Benefits
Struvite has a very slow nutrient release rate
Reduced nutrient runoff
Reduced eutrophication in lakes, rivers, and aquifers
Uptake rate of phosphorous of struvite is 100%
Greater phosphorus concentration in struvite treated plants
Reduced waste storage overflow

8.2 Project Planning and Development: Gantt Chart

This is the overview of the planning and direction using the Gantt program that led to the completion of this project. The steps, dependencies, dates, and important design solutions are included in this chart.