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Comparison of Phosphorus Removal and Recovery Methods and Proposed Design of High Rate Algal Pond for Swine Wastewater

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BY

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This Design Paper is approved as a creditable and independent investigation by a candidate for the Master of Science degree and is acceptable for meeting the design paper requirements for this degree. Acceptance of this design paper does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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Design Problem Statement

High phosphorus concentrations in wastewater effluent can have harmful effects to aquatic environments and water quality. An excess of nutrients such as phosphorus in water bodies will cause eutrophication, which depletes the available oxygen within the water and is detrimental to aquatic life. Additionally, phosphorus leaching from wastewater discharge has negative impacts to groundwater quality. The depletion of phosphorus as a natural resource is also of concern as phosphorus is an essential product for agricultural and industrial production. Phosphorus is a non-renewable resource, and natural sources are becoming more difficult and expensive to access. Therefore, the removal and recycle of phosphorus from wastewater is an important area of research.

Several methods of phosphorus removal and recovery as part of the wastewater treatment process exist and are applicable on a practical scale. Livestock wastewater streams, such as swine wastewater, have particularly high concentrations of phosphorus which makes them good candidates for phosphorus recovery processes. This study compares existing phosphorus removal methods and selects a proposed treatment technology for an assumed swine production facility.

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1. Introduction

The removal and recovery of phosphorus in waste is a significant area of interest in wastewater treatment for two primary reasons: the recycle and utilization of phosphorus as a resource and the detrimental effects of this nutrient to the environment. The removal of phosphorus from wastewater effluents is critical to the health of the environment and aquatic life as well as the quality of potable water supplies (Hanhoun et al., 2011). An overabundance of nutrients such as nitrogen (N) and phosphorus (P) will cause eutrophication, which is an excess of growth of cyanobacteria and algae in natural waters (Qui and Ting, 2014). Eutrophication reduces the oxygen available in waterbodies and is harmful to aquatic life. Discharge of wastewater with high N and P concentrations puts surface water sources at increased risk of eutrophication.

N and P leaching from wastewater discharge or agricultural applications also negatively impacts the quality of groundwater sources. (Saarijarvi et al., 2004). The USEPA National Pollutant Discharge Elimination System (NPDES) sets national guidelines for N and P nutrient effluent limits and monitoring requirements to reduce nutrient loading and protect local and downstream water quality. According to data collected in February of 2016, of the 56 U.S. states and territories that are under the jurisdiction of the USEPA, 51 have facilities with N and/or P monitoring requirements and 46 have municipal sewage treatment facilities with numeric effluent limits for N and/or P (USEPA, 2016). These effluent limits and nutrient monitoring requirements show that phosphorus removal processes are already a consideration for many facilities across the country and emphasize the importance of efficient phosphorus removal from municipal and agricultural wastewater. Phosphorus removal is an important consideration for animal wastewaters in particular, since land application of animal wastes with high phosphorus concentrations can cause the soil to become oversaturated with soil, increasing soil erosion potential (USPEA, 2004). High concentrations of phosphorus in animal wastes are a concern in many regions throughout the United States, as shown in Figure 1. Therefore, phosphorus removal from wastewater streams containing livestock waste is essential for maintaining soil and groundwater quality.

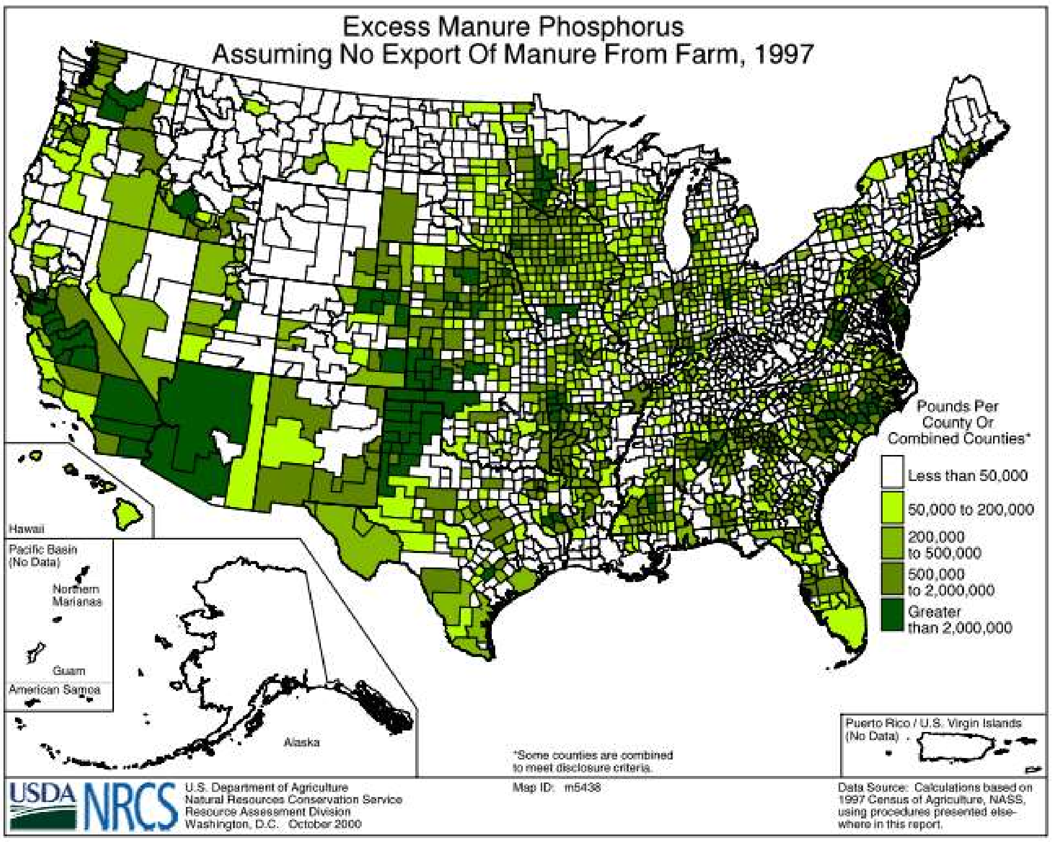

Figure 1. Counties with Animal Manure Containing Excess Phosphorus (USEPA, 2004)

In addition to removal, the potential for phosphorus recovery and recycle from wastewater is a valuable area of research, as phosphorus is an essential nutrient to agricultural and industrial production and is a non-renewable resource. Currently, most phosphorus as phosphate is utilized in mineral fertilizers (Cordell et al., 2009), but the mining of phosphate rock is quickly becoming more expensive as natural supplies are depleted. Phosphate recycle is therefore an important concept because the known supplies of phosphate rock are expected to be exhausted within the next three decades (Cordell et al., 2011). It has been estimated that 15-20% of global phosphorus demand could be satisfied by the nutrient's recovery from municipal wastewater (Yuan et al., 2012). The recovery potential of phosphorus from livestock and other agricultural wastewaters is even higher than this estimate, as agricultural wastewaters typically contain phosphorus concentrations much higher than those in domestic wastewaters (Yuan et al., 2012).

1.1 Purpose and Scope of Study

Numerous studies have investigated methods for phosphorus removal that may be applicable for large municipal and industrial wastewater treatment facilities, but these methods are often not feasible for small facility operation due to concerns of cost and complex operation. Few studies have explored methods that may be attainable for smaller, rural wastewater treatment facilities and/or livestock producers that may be required to treat their own wastewater. This review compares existing and developing phosphorus removal and recovery methods through the perspective of feasibility for smaller facilities. For the purpose of this review, small treatment wastewater treatment facilities are defined as those serving a population of less than 10,000 and livestock wastewater is defined as waste streams produced by confined animal feeding units (typically producing either cattle or swine) with high concentrations of phosphorus. Following the comparison of treatment methods for phosphorus removal and recovery, each method is evaluated for its specific applicability for the treatment of wastewater from an assumed swine production facility located in eastern South Dakota. A proposed design of the recommended treatment system is presented for the assumed facility.

1.2 Overview of Study Contents

Several physical, chemical, and biological methods for phosphorus removal from wastewater are researched and presented including chemical precipitation, adsorption and ion exchange, membrane processes, enhanced biological phosphorus removal (EBPR), constructed wetlands, and algae utilization. Each of these methods is evaluated based on six factors to determine their feasibility for small facilities and ability to effectively treat livestock wastewater. These factors include capital and operational costs, ease of operation and maintenance, and reuse potential of recovered phosphorus as fertilizer. These three factors are determined to be the most important in determining applicability for small systems, because these facilities often have limited resources in terms of funds and staffing to handle process costs and operation. Also, rural facilities are typically the facilities that have the easiest access to areas of agricultural production meaning that reuse of phosphorus products as fertilizer would be the most ideal recovery method. The remaining factors of comparison between phosphorus removal methods include the efficiency of phosphorus removal and recovery, the availability of the treatment technology, and the spatial requirements of each method (e.g., process footprint).

2. Physical and Chemical Methods for Phosphorus Removal and Recovery

2.1. Chemical Precipitation

2.1.1. Process Overview

The process of chemical precipitation, also referred to as crystallization, is utilized to recover dissolved phosphorus in its liquid phase. Precipitation requires a sufficient concentration of phosphates in the wastewater to yield thermodynamic super-saturation (Rittmann et al., 2011) meaning that pretreatment steps such as membranes are typically needed for more dilute wastewater sources like municipal waste (Peng et al, 2018). Livestock wastewaters such as swine wastewater have naturally high phosphate concentrations making them a viable candidate for phosphorus removal by precipitation. Under the right conditions, phosphorus precipitation in wastewater can occur naturally. However, initiating this process during wastewater treatment typically requires pH adjustment and the addition of metal ions (Rittmann et al., 2011). The most common ions used for phosphorus recovery are magnesium (Mg^{2+}) and calcium (Ca^{2+}) that are added to the wastewater via chemical solutions. The phosphate precipitates formed using magnesium and calcium ions are typically struvite (also referred to as magnesium ammonium phosphate or MAP) and calcium phosphate, both of which can be utilized directly as fertilizers.

There are several factors that affect the efficiency of the precipitation process, as well as the purity of the products formed. The pH of the precipitation solution is considered to be one of the most important parameters influencing the yield, size, and purity of the recovered phosphates because it can influence the concentration of free ammonia and phosphate (Bi et al., 2014) and the solubility of the precipitates (Huang et al., 2015). Therefore, the pH should be adjusted to between 8-10 to facilitate the formation of phosphate products such as struvite (Y. Ye et al., 2016). Other significant factors include the molar ratio of the ions in the solution because of its effect on the solution supersaturation level and the mixing intensity of the reactor due to its effects on the crystal growth process (Peng et al, 2018).

The general phosphorus precipitation process is shown in the schematic below (Figure 2). Wastewater with a sufficient phosphorus concentration enters a basin and solutions containing the required Mg^{2+} and Ca^{2+} are added to the reactor. This process can be incorporated into existing treatment processes, as precipitating chemicals can be added before, after, or during conventional biological treatment (X. Ye et al., 2016). If pH adjustment of the wastewater is needed, additional chemicals such sodium hydroxide (NaOH), lime (CaO), or carbon dioxide (CO_2) can also be added (Peng et al, 2018). The wastewater undergoes a period of mixing within the reactor to allow precipitation of particles to occur after which the formed products of calcium phosphate and/or struvite are removed and utilized as a source of recovered phosphorus. The addition of seed materials (e.g., sand, anthracite, clay, or pre-formed struvite particles) to the reactor can improve the efficiency of phosphorus precipitation (Rittmann et al., 2011).

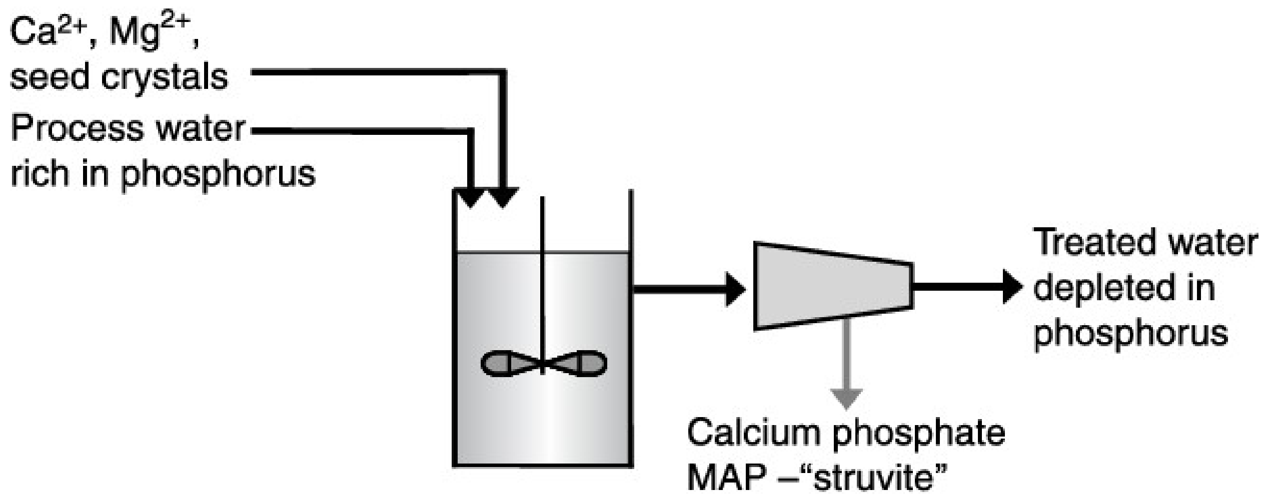

Figure 2. Process schematic of phosphorus recovery via precipitation (Cornel & Schaum, 2009)

2.1.2. Evaluation of Chemical Precipitation for Small Facilities

The first factor that should be analyzed when evaluating phosphorus precipitation as struvite or calcium phosphate as a treatment method for small facilities is cost. The costs associated with precipitation include capital costs of the reactors and product recovery processes. While these costs may be comparable to other treatment methods, the precipitation process also requires high operation and maintenance costs due to the need to feed large amounts of chemicals to supply the magnesium and calcium ions as well as energy costs for mixing in the reactor (Y. Ye et al., 2016). The processes of chemical addition and precipitates handling can typically be easily managed as part of the operation and maintenance processes for this treatment method.

An important advantage for rural facilities when considering this method for phosphorus recovery is that the recovered products of struvite and calcium phosphate can be used directly as effective fertilizers (Peng et al, 2018) and do not need to be converted to other compounds. Struvite can also be used in the production of other commercial and industrial products. Additionally, process of chemical precipitation can produce phosphorus removal rates of upwards of 90% (Shih et al., 2017). Precipitation is most efficient at high influent phosphorus concentrations, meaning that this method is particularly effective for phosphorus recovery from livestock wastewaters. This process does not typically require a significant amount of space and can be performed within the footprint of a traditional wastewater treatment facility. Precipitation of phosphorus in wastewater treatment is also one of the most common methods of phosphorus removal, so there are several commercial technologies available for this process including PHOSNIX, Rem-Nut, and Ostara (Schröder et al., 2010) as well as Struvia^{TM} and PHOSPAQ^{TM}.

2.2. Adsorption and Ion Exchange

2.2.1. Process Overview

The processes of adsorption and ion exchange involve the transfer of dissolved substances onto or within other materials and are generally considered to operate similarly for the purpose of phosphorus removal and recovery. Adsorption is defined as the transfer of solutes in liquid to solid absorbents (Crittenden et al., 2005). Adsorbents in the wastewater treatment process are typically used as filter or bed media (Loganathan et al., 2014), and the process of adsorption via filtration can sometimes be aided with coagulation (Rittmann et al., 2011). In the process of coagulation, the phosphorus particulates in the wastewater are attracted to the added coagulant, and the particles form precipitates that can then be adsorbed. Adsorption via filter media occurs when the dissolved substance is adsorbed and collected by the media particles, therefore removing the phosphorus as the wastewater passes through the filters. The use of adsorption via coagulation and filtration processes are common in wastewater treatment and these processes have been utilized for decades.

In the ion exchange process, undesirable ions can be exchanged for solid-phase ions based on ion affinity (Crittenden et al., 2005). Compared to adsorption, ion exchange can provide a more selective method of separating specific ions from the solution (Rittmann et al., 2011). Ion exchange involves one ion being absorbed onto the sorbent or ion exchanger while another ion is desorbed (Loganathan et al., 2014), and is therefore frequently considered to be a type of adsorption. Ion exchange resins are used as a type of filter media and therefore remove phosphorus in the wastewater as it passes through the filters. The ion exchange process is generally reversible (Kuzawa et al., 2006) and is therefore thought to be advantageous for phosphorus removal and recovery.

To achieve recovery of the phosphorus particles that are transferred to absorbents such as filter media after adsorption or ion exchange, the absorbents must undergo regeneration (also called desorption). Regeneration is the process by which the molecules (such as phosphate) that are bound on the loaded absorbent are released to recover the molecules and replenish the active sites of the absorbents so they can be reused (Suresh Kumar et al., 2019). The regeneration tank then contains a concentrated solution of phosphate particles. To recover the removed phosphate as a useable product, this solution must undergo an additional recovery process such as precipitation (Loganathan et al., 2014). A schematic of the adsorption process, including regeneration, is shown below in Figure 3.

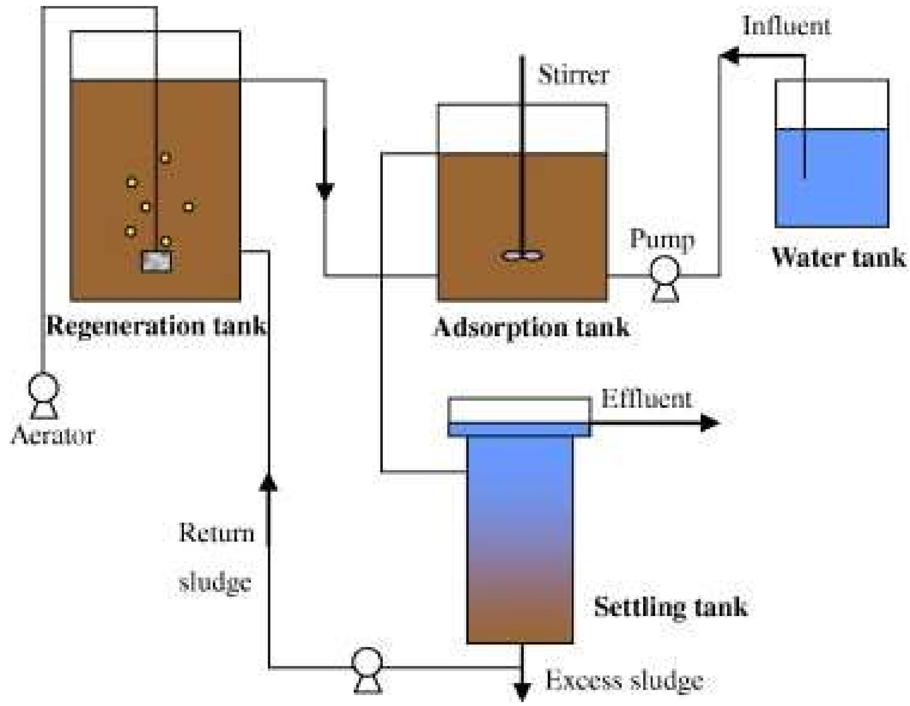

Figure 3. Process schematic of the adsorption and regeneration process (Lui et al., 2011)

2.2.2. Evaluation of Adsorption and Ion Exchange for Small Facilities

When evaluating this treatment method for phosphorus removal and recovery in small utilities, the first factor that should be evaluated is cost. Since adsorption and ion exchange can be performed as part of the traditional coagulation/sedimentation/filtration treatment process, the capital costs associated with this method are relatively low. Additionally, several low-cost absorbents are available and effective (Cueto and Hanson, 2019) so the typical operation and maintenance costs for this process are low. However, additional processes are frequently required to convert the desorbed phosphate ions into a material that can be recovered and utilized as a fertilizer and these processes increase the process costs. These processes also increase the difficulty of operation for the adsorption/ion exchange process, which on its own is easily operated. As previously stated, the phosphorus recovery potential of this method is lower than other treatment processes. The products removed with from adsorption via filter media secondary processes such as precipitation must be applied to the regeneration solution to recover the phosphates in a usable form.

In terms of removal efficiency, the adsorption and ion exchange treatment methods can reach 75-90% removal efficiency under favorable conditions (Cueto and Hanson, 2019), including influent streams with high phosphorus concentrations such as livestock wastewater. Since these processes can be performed as part of traditional wastewater treatment processes, the required footprint is minimal. Wastewater treatment via adsorption and ion exchange is common and easily accessible, which is an advantage for small or rural facilities.

2.3. Membrane Processes

2.3.1. Process Overview

A physical treatment method that is commonly used in water and wastewater treatment to remove particulates and dissolved materials is membrane processes. Most tertiary membranes processes in wastewater treatment are used as pressure driven separation processes (Obotey Ezugbe and Rathilal, 2020) meaning that the wastewater is forced through layers of membranes under significant pressure to separate particulates and dissolved materials from the water. There are several types of membranes that are used in wastewater treatment, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) membranes. The difference between each type of membrane is the pore size and amount of pressure required, with MF membranes having the largest pore size and the lowest pressure and RO membranes having the smallest pore size and the highest pressure requirement (Obotey Ezugbe and Rathilal, 2020).

When membranes are incorporated into a wastewater treatment process, they are typically used in place of filtration to remove contaminants. Membrane processes such as nanofiltration can be used as a tertiary treatment following pretreatment steps to separate certain particulates from wastewater streams. In the nanofiltration process, the wastewater is pumped at high pressure through semi-permeable membranes to prevent substances such as phosphorus from passing through the membranes, thus removing them from the treated water (USEPA, 2021). The phosphorus is then concentrated within the membrane reject water, and additional recovery methods can be applied to this waste stream.

As previously stated, nanofiltration is typically used as a tertiary treatment process, meaning that this method of phosphorus recovery requires pretreatment such as activated sludge and sedimentation, or precipitation (Chon et al., 2012). Membrane filtration can also be used as part of a membrane bioreactor system. This system combines a suspended growth biological reactor with solids removal via filtration (USEPA, 2007). Membranes are used after a bioreactor to remove phosphorus and other contaminants and are typically vacuum-driven and operated at a very low pressure. The rejected nutrients are then enriched within the concentrate water, and the phosphorus-rich solution is used for phosphorus recovery. For both nanofiltration processes and membrane bioreactors, the phosphorus in the reject solution can be sometimes recovered via natural precipitation without requiring addition of magnesium and calcium (Qui and Ting, 2014). However, chemically aided precipitation is sometimes needed to convert the removed precipitation into a useable form. Figure 4 below shows a process schematic of how membranes are integrated into wastewater treatment processes.

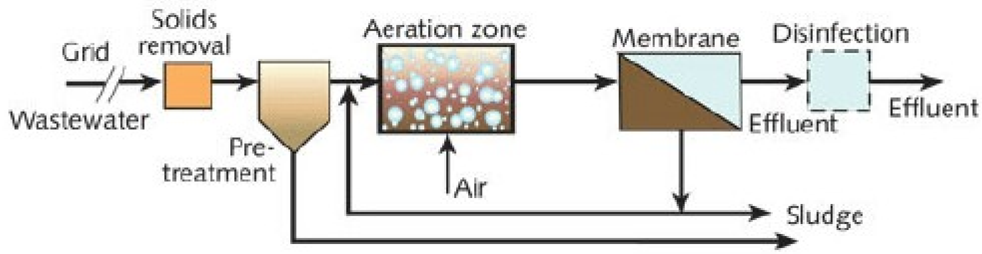

Figure 4. Wastewater treatment process schematic using membranes as tertiary treatment (Pandey and Singh, 2014)

2.3.2. Evaluation of Membrane Processes for Small Facilities

The first factor that should be analyzed when evaluating membrane processes as a treatment method for small utilities is cost. This process has a high capital cost, as membranes for wastewater treatment are an expensive technology. Membrane processes also have a high overall maintenance cost due to membrane cleaning and fouling control as well as eventual membrane replacement (USEPA, 2007). Due to frequent cleaning requirements, membrane processes are more difficult to operate overall than conventional processes. Additionally, since membrane processes require pretreatment, this can increase the overall process costs and operation complexity. This process is not typically feasibly as a stand-alone process for phosphorus removal and recovery.

Membrane processes do not have a good direct phosphorus recovery potential, and precipitation (either natural or chemically aided) is required to recover phosphorus from the supernatant in a form that can be utilized as a fertilizer. However, nanofiltration as tertiary treatment can have a high rate of phosphorus removal with one study showing an 80-90% removal rate of phosphates (Chon et al., 2012). Membrane processes require less space compared to conventional treatment systems and therefore the process has a small footprint

(USEPA, 2007). However, since this treatment method for phosphorus recovery is an emerging technology in recent decades it is not easily accessible or commercially available.

3. Biological Methods for Phosphorus Removal and Recovery

3.1. Enhanced Biological Phosphorus Removal

3.1.1. Process Overview

A widely applied method of biological phosphorus removal from wastewater is the process of enhanced biological phosphorus removal (EBPR). This process utilizes a group of bacteria referred to as polyphosphate accumulating organisms (PAOs) to take up phosphorus from wastewater in amounts greater than their growth requirements when growing under alternating anaerobic and aerobic/anoxic conditions (Tchobanoglous et al., 2003). The excess phosphorus that is taken up by the PAOs is stored as intracellular granules of polyphosphate, therefore converting the diluted phosphorus in wastewater into concentrated bacterial sludge (Yuan et al., 2012). When this sludge is separated from the treated wastewater, it can be utilized as a source of recovered phosphorus.

As previously stated, the operation of the EBPR process requires alternating anaerobic and aerobic/anoxic conditions. This can be achieved by either controlling the time periods of each treatment condition in a batch reactor system or by flowing the wastewater through a series of basins that are set as anaerobic, anoxic, and aerobic zones as part of a continuous system (Yuan et al., 2012). To grow and take up phosphorus effectively PAOs require organic carbon, so the wastewater source must have sufficiently high BOD concentrations (Rittmann et al., 2011). The sludge recovered from EBPR systems can be utilized directly as a fertilizer through land application. This phosphorus-rich sludge can contain 5-7% phosphorus, which is a significantly higher concentration than the 1-2% concentration of normal activated sludges (Yuan et al., 2012). Schematics of two EBPR processes are shown below in Figure 5.

Efficient operation of EBPR systems must include precautions to control the growth of competing organisms. Controlling the growth of glycogen accumulating organisms (GAOs) is a significant challenge for achieving a successful EBPR system (Oehmen et al., 2007). Managing factors such as temperature and pH can influence the competition between PAOs and GAOs, but previous studies have concluded that maintaining a desirable carbon source (e.g., acetate vs. propionate) in the wastewater is the most effective way to reduce the growth of GAOs (Lopez-Vazquez et al., 2009).

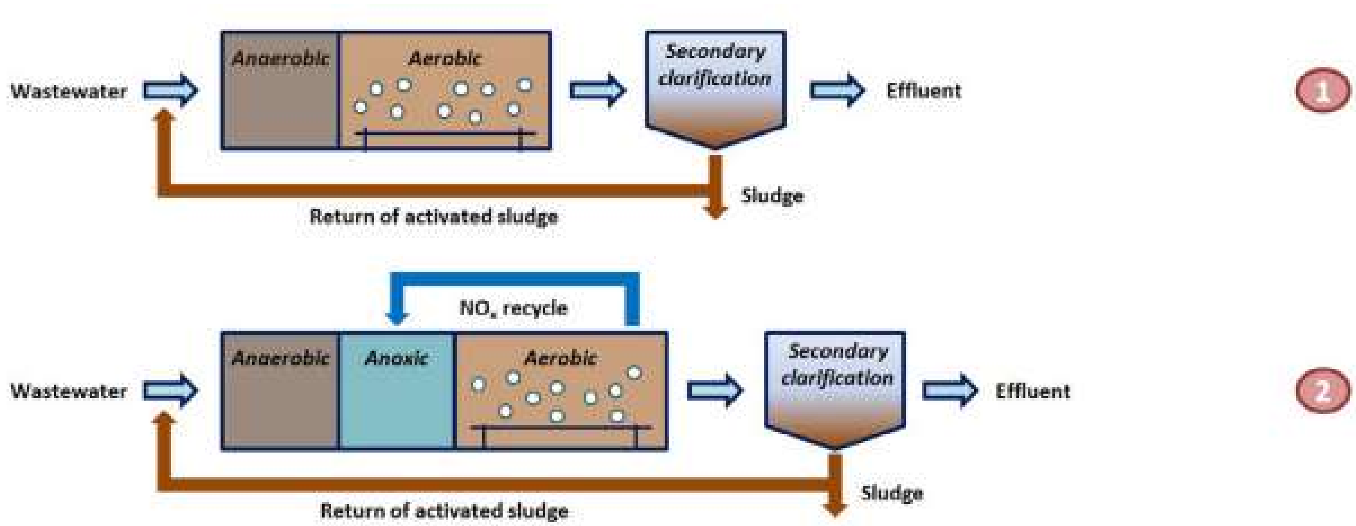

Figure 5. EBPR Processes: 1 – basic EBPR process (A/O process); 2 – A^2O process (Tarayre et al., 2015)

3.1.2. Evaluation of EBPR for Small Facilities

When evaluating this EBPR treatment systems for phosphorus removal and recovery in small utilities, the first factor that should be evaluated is cost. Overall, EBPR systems are relatively low cost. Depending on the design or layout of the basins for anaerobic/aerobic/anoxic zones, the capital cost of the process is likely similar to conventional processes. However, since this process does not require chemical addition or other frequent maintenance, operation and maintenance costs are low. In terms of process operation, due to the requirement of alternating anaerobic/aerobic/anoxic conditions, operation of EBPR systems is complex. This process also requires specific management of operating conditions to prevent growth of competing organisms (Oehmen et al., 2007) to keep the process effective at phosphorus removal. EBPR systems have a high phosphorus reuse potential, as the sludge recovered from this process can be used directly as an agricultural fertilizer.

EBPR systems can be highly effective at phosphorus removal for livestock wastewaters with a removal rate of greater than 90% reported in most studies (Yuan et al., 2012). However, because phosphorus removal and recovery are dependent on how much phosphorus the PAOs are able to take in, the efficiency of EBPR can vary based on process conditions. The required footprint of EBPR can vary depending on basin layouts but can be comparable to conventional treatment methods. Since EBPR is not as commonly used as a treatment method, it is not commercially available and is less accessible than other methods discussed in this review.

3.2. Algae Utilization

3.2.1. Process Overview

The use of phototrophic microorganisms like algae in facultative ponds is a common wastewater treatment practice due to their ability for cost effective treatment of carbon and pathogenic pollutants (Shilton et al., 2012). However, phosphorus removal in typical ponds is variable and is not usually optimized for biomass productivity. High rate algal ponds can have higher biomass productivity and therefore higher phosphorus uptake than conventional wastewater treatment ponds (Shilton et al., 2012). In high rate algal ponds, the algae are grown at the surface of shallow, gently mixed ponds with shorter detention times than traditional facultative ponds. The extent of the phosphorus removal of high rate ponds is a function of light intensity, temperature, and influent phosphorus concentrations. High rate algal ponds are typically utilized as a polishing step for additional nutrient removal after traditional pretreatment methods.

A study by Richmond showed that the phosphate content of algal dry biomass grown in high rate ponds could reach up to 3.3%, which is higher than the 1% content typically achieved in ‘normal’ pond algal biomass (2004). The biomass produced by algae is therefore rich in phosphorus and can be harvested from the ponds to be utilized as a direct application fertilizer (Shilton et al., 2012). Figure 6 shows the layout of a typical high rate algal pond. In these types of ponds, the flow is typically routed along baffle walls to form a raceway flow pattern. The flow is also agitated with a paddle wheel to encourage gentle mixing to blend the influent with the wastewater flow already in the pond and to maintain a constant flow velocity (LGASA, 2020). Carbon dioxide (CO_2) is also added to control the pH in the pond and provide a sufficient carbon source for algae growth (Couto et al., 2021). Studies have shown that the addition of carbon dioxide can double microalgae productivity in high rate algal ponds (Park and Craggs, 2010). Biomass growth and harvesting must be maximized to achieve successful phosphorus recovery (Shilton et al., 2012). The higher biomass concentration in high rate algal ponds helps facilitate gravity harvesting of the biomass. Additionally, a study by Park et al. found that harvesting efficiency could be enhanced to greater than 85% if a proportion of the biomass is recycled (2011).

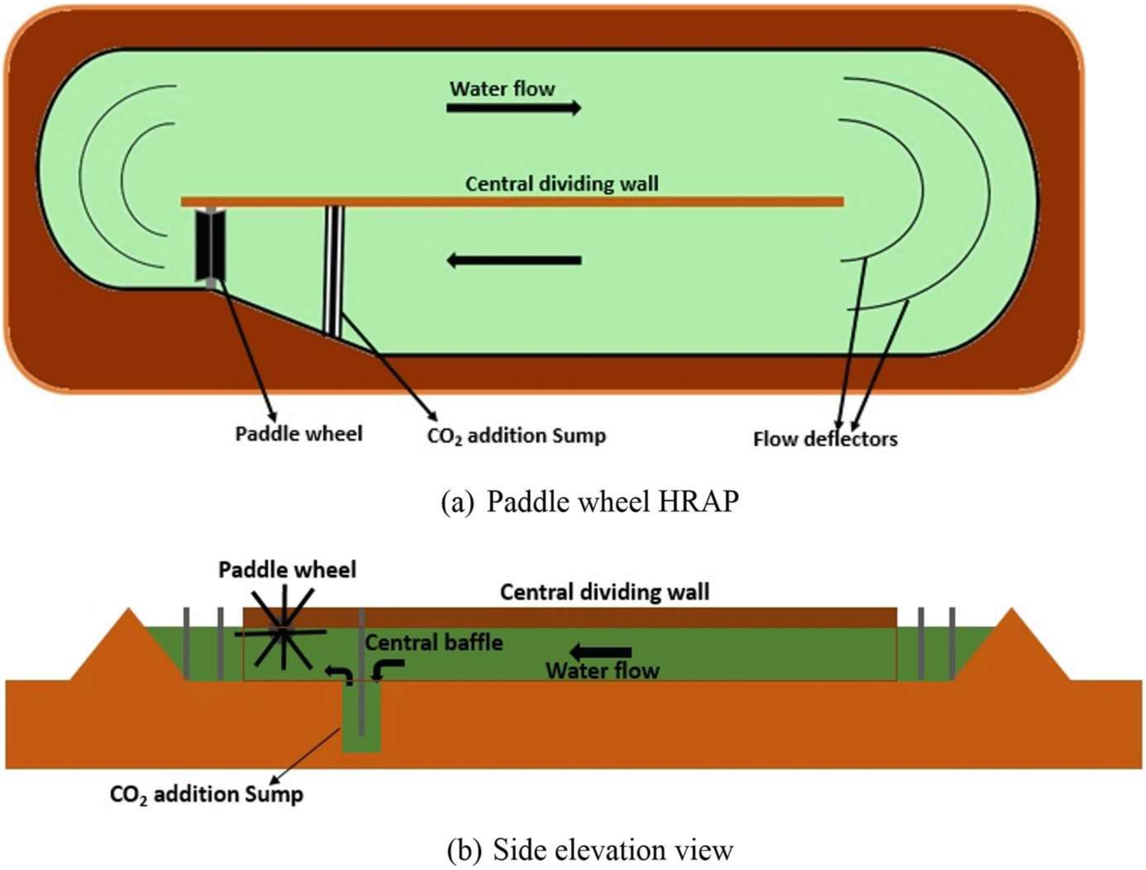

Figure 6. Typical layout of a high rate algal pond (HRAP) (Ranjan et al., 2019)

Another method of utilizing phosphorus uptake in algae is the implementation of a photobioreactor, which is a bioreactor that utilizes a light source to cultivate microorganisms such as algae (Znad, 2020). Photobioreactors can be operated in numerous configurations, as shown in Figure 7. High rate algae ponds can be considered photobioreactors (see Figure 7a), but the term is typically used to describe a closed system. Closed-system photobioreactors function in essentially the same way as high rate algae ponds. Microalgae are cultivated within the reactor, and the organisms' uptake of phosphorus is utilized as a removal and recovery method. Photobioreactors require the addition of various nutrients necessary for algae growth and typically require an artificial light source (Znad, 2020). Photobioreactors have the benefit of requiring a much smaller footprint than algae ponds with high biomass production (Elawwad et al., 2017), however they can have higher construction and operation costs.

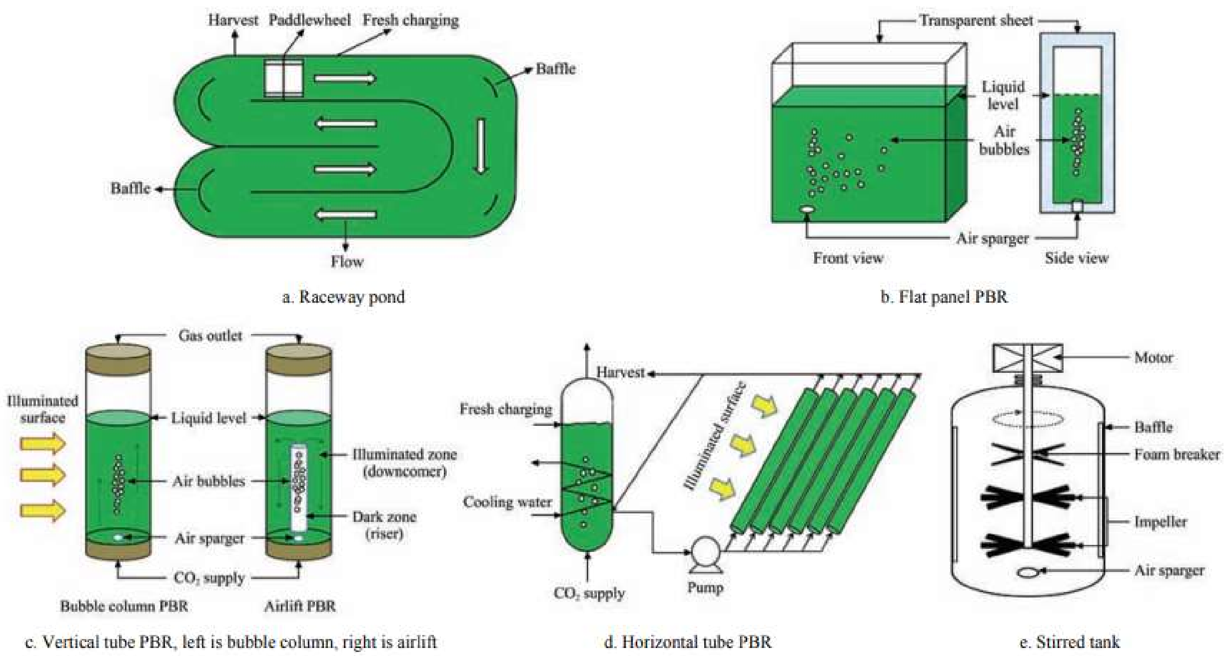

Figure 7. Schematics of various types of photobioreactors (PBRs) for microalgae cultivation (Lu et al., 2017)

3.2.2. Evaluation of Algae Utilization for Small Facilities

Algae utilization as a method for phosphorus recovery for small treatment facilities is a low-cost process. There is minimal equipment required for this process, and since algal ponds do not require chemical addition there are also minimal operation and maintenance costs associated with this process. Algal ponds are also simple to operate and typically only require management of biomass harvesting. Algae utilization processes have a high potential of phosphorus reuse, as the biomass produced by the algae can be harvested and utilized as a direct application agricultural fertilizer (Shilton et al., 2012).

Algal processes can be less efficient than other processes at overall phosphorus removal, which is a disadvantage for treating livestock wastewaters with high phosphorus concentrations. Phosphorus removal rates can vary based on algae growth, species, and uptake, but some studies have found phosphorus removal rates by microalgae of up to 78% (Abdel-Raouf et al., 2012). The use of algal ponds as wastewater treatment is a common process and the process is easily available and constructable. Algae utilization methods, particularly algal ponds, do require significant amounts of space and have a large footprint compared to the previously discussed physical treatment processes. However, high rate algal ponds require significantly less land area than a conventional wastewater treatment pond.

3.3. Constructed Wetlands

3.3.1. Process Overview

Like algae, the growth of macrophytes (e.g., aquatic plants) in ponds and wetlands can also result in phosphorus removal from wastewater. Several types of aquatic plant species can be grown together to create constructed wetlands. Floating macrophytes, such as water hyacinth and duckweed, grow on the surface of treatment ponds while emergent macrophytes, such as various types of reeds and cattails, grow through the water column with their roots and stems submerged (Shilton et al., 2012). Emergent macrophytes are most common in constructed wetlands. Some constructed wetlands that utilize these plants include a floating mat so that the roots of the plants grow down through the water column and provide a large surface area for biofilm development (Tanner and Headley, 2011). Constructed wetlands can be operated in various configurations including both horizontal and vertical flow. Phosphorus removal within constructed wetlands occurs via uptake in the macrophytes themselves as well as through the biofilm that grows around the plants and on the surface of the water. Constructed wetlands can also be used as a polishing step for conventionally treated wastewater (Cheng et al., 2020). This process is shown in Figure 8.

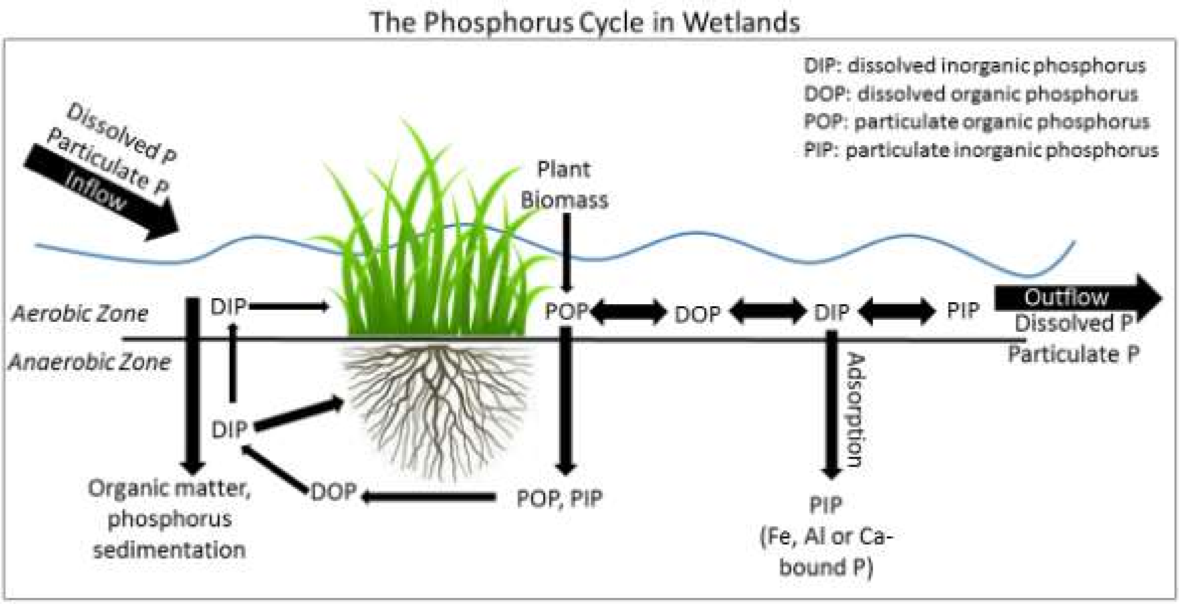

Figure 8. Illustration of the phosphorus cycle in wetlands (Ziegler, 2016)

3.3.2. Evaluation of Constructed Wetlands for Small Facilities

Like algae utilization processes, constructed wetlands as a method for phosphorus recovery for small treatment facilities is a low-cost process. There is minimal equipment and no chemical addition required for wetlands, so there are little to no operation and maintenance costs for wetlands. They also require minimal management and are simple to operate. Biomass and decaying plants from constructed wetlands can be utilized as an agricultural fertilizer, but it can be more difficult to harvest these materials from wetlands than from other pond systems.

Constructed wetland systems are the least efficient at overall phosphorus removal when compared to the other methods analyzed in this review. However, these systems can still achieve sufficient removal for wastewater discharge as they can achieve 30-70% phosphorus removal based on system conditions (Shilton et al., 2012). Like algal ponds, constructed wetland processes are common, available, and easily constructable and have a large spatial footprint.

4. Methods Treatment Process Selection for an Assumed Swine Production Facility

The previous Sections 2 and 3 introduced various phosphorus removal and recovery processes for livestock wastewaters, and the applicability of each process for small to medium livestock facilities was evaluated generally. However, the application of each process will depend on the conditions of a specific facility such as facility size, location, budget, climate, land availability, and effluent regulations. In this section, the processes of chemical precipitation, adsorption and ion exchange, membrane processes, EBPR, constructed wetlands, and algae utilization are compared and evaluated based on an assumed swine production facility located in eastern South Dakota. The recommended treatment process for this facility is selected based on a series of factors that have been weighted by order of importance to this facility. A proposed design for the recommended treatment process is presented in Section 5.

4.1. Assumed Swine Production Facility and Wastewater Characteristics

The assumed swine production facility is located in rural eastern South Dakota and has no limitations in terms of land availability for a wastewater treatment process. The average temperature in for eastern South Dakota ranges from approximately 0°F to 80°F, and the average annual temperature is approximately 40°F or 5°C (U.S. Climate Data, 2022). Eastern South Dakota consists of mostly agricultural farmland, meaning that land application of treated wastewater is assumed to be a feasible method for residuals management and disposal. This facility is assumed to have no effluent phosphorus discharge limits following its wastewater treatment processes.

The assumed swine production facility is a concentrated animal feeding operation (CAFO) that houses finisher pigs, which have a typical weight range of 60-250 pounds per animal (USEPA, 2004). For this study, an average weigh of 155 pounds per animal is used for all calculations. The assumed swine production facility has a capacity of 1,000 animals and is classified as a medium-size facility based on the EPA CAFO regulations (2004). Therefore, the total animal weight produced by this facility is 155,000 pounds. Finisher pigs in CAFOs have a typical wastewater generation rate of 132 lb/day per 1000 lb of animal weight (USEPA, 2004) which converts to 2.1 ft^3/d per 1000 lb. Therefore, the assumed swine facility would produce a daily wastewater flow of 328 ft^3/d. The typical wastewater quality characteristics for swine wastewater including BOD_5, nitrogen (N), and phosphorus (P) concentrations are shown below in Table 1 (USEPA 2004). The calculated concentration of each parameter in mg/L is converted from the given concentration in lb/d.

Table 1. Typical Swine Wastewater Quality Parameters

	BOD_5	N	P
Given Concentration (lb/d)	4.79	0.45	0.33
Calculated Concentration (mg/L)	36,304	3,411	2,501

4.2. Process Selection for Treatment of the Assumed Swine Facility Wastewater

To determine the recommended treatment process for removal and recovery of phosphorus, six factors have been selected and weighted by the assumed order of importance to this swine facility. The six factors include (1) treatment process costs, (2) ease of operation and maintenance, (3) reuse potential of the recovered phosphorus as fertilizer, (4) phosphorus removal and recovery efficiency, (5) process availability, and (6) process footprint as shown in Table 2. Each factor is weighted on a scale of 1 (least important) to 3 (most important). The treatment processes were rated on a scale of 1-5 for each factor, with 1 being the worst and 5 being the best. Table 2 shows a decision matrix that tabulates the rankings for each treatment process for the factors described in this section.

Table 2. Decision Matrix to Select the Treatment Process for the Assumed Swine Production Facility

Factor	Weight	Chemical Precipitation	Adsorption & Ion Exchange	Membrane Processes	EBPR	Algae Utilization	Constructed Wetlands
(1) Capital and Operation Costs	3	3	3	2	4	5	5
(2) Ease of Operation and Maintenance	3	4	4	2	2	5	5
(3) Reuse Potential of Recovered Phosphorus as Fertilizer	3	5	2	2	4	5	3
(4) Efficiency of Phosphorus Removal and Recovery	2	5	4	4	3	3	2
(5) Process Availability	2	3	3	3	5	4	4
(6) Process Footprint	1	5	5	5	4	2	2
Total		**57**	**46**	**37**	**50**	**61**	**53**

Processes are rated on a scale of 1 (worst) to 5 (best).

The first factor of the treatment process cost includes both capital and operational costs, and this factor was weighted as the highest scale of 3. A treatment process with low construction and maintenance costs would be important to rural facilities such as the assumed swine production facility because of limited resources and funding options in rural areas. A study performed by Bashar et. al (2018) was used as the basis for the cost evaluation of the treatment processes. The study evaluated various phosphorus removal processes based on operation and maintenance costs including energy and chemical requirements, sludge disposal, and process maintenance. The study included the processes of precipitation, adsorption via filtration, membrane processes, and EBPR. The study showed that the costs of phosphorus removal via membrane processes were the highest, with adsorption via filtration and precipitation having similar, lower costs, and EBPR having the lowest cost. This study did not include capital costs for each process, but typical capital costs follow the same trends. Membrane processes have the highest capital costs due to pretreatment requirements. Precipitation and adsorption/ion exchange processes have lower capital costs than membrane processes, and capital costs for these processes include reaction tanks, chemical feed, and control systems. EBPR processes have lower capital costs than the physical/chemical processes because they do not require chemical feed systems. The ratings for these processes for the factor of cost have been rated in Table 2 to reflect the results of the study by Bashar et. al (2018). The processes of algae utilization and constructed wetlands were not included in this study. These processes do not have chemical requirements and have minimal energy, sludge disposal, and maintenance costs and have low capital costs. Therefore, they are rated highest at the scale of 5 for cost effectiveness.

The second factor in Table 2 is ease of operation and maintenance. Like the capital and operation costs, this factor is weighted as the highest scale of 3 due to the limited resources and technical skills required to operate the treatment process for the assumed swine production facility. As discussed in Sections 3.2.2 and 3.3.2, algae utilization processes and constructed wetlands are both simple to operate and require minimal maintenance. Both processes require minimal or no chemical addition and have minimal, if any, mechanical equipment that would require operator maintenance. Therefore, both processes are rated highly as the scale of 5 for this factor. Chemical precipitation and adsorption/ion exchange are both traditional treatment processes that have relatively simple operation and maintenance, as discussed in Sections 2.1.2 and 2.2.2. These processes are rated as the scale of 4. For this rating, it is assumed that the precipitation process would be using an alum or ferric coagulant, as phosphate precipitation as struvite is a newer technology that requires high technical skills. The treatment processes of EBPR and membranes both have complex operation and maintenance considerations, meaning that these processes have been rated lowest as the scale of 2 for this factor. Membrane treatment requires high technical skills to operate and maintain the pretreatment and cleaning processes and to prevent membrane fouling (USEPA, 2007). The EBPR process also requires high technical skills to optimize the alternating anaerobic/aerobic/anoxic conditions to prevent growth of competing organisms (Oehmen et al., 2007).

The third factor evaluated in this section is the reuse potential of each treatment method to utilize the recovered phosphorus as an agricultural fertilizer. This factor is highly weighted at the scale of 3 because land application of treated wastewater as fertilizer is the most feasible method for residuals management and disposal for the assumed swine facility. The processes of algae utilization and chemical precipitation are the highest ranked at the scale of 5 for this factor because both methods produce products that can be directly applied as a fertilizer without needing to be converted into other forms, as discussed in Sections 2.1.2 and 3.2.2. The sludge recovered from EBPR can also be directly utilized as a fertilizer, so this treatment processes was rated highly at the scale of 4 for this factor as well. The recovery process for the phosphorus removed by constructed wetlands is more difficult than other processes, as some of the phosphorus is taken up by macrophytes, so this process was rated lower at the scale of 3. The processes of adsorption/ion exchange and membrane treatment both require secondary treatment of recovered phosphorus products to convert them into a form usable as fertilizer, as discussed in Sections 2.2.2 and 2.3.2. Therefore, these processes were rated the lowest at the scale of 2 for this factor.

The next factor considered is the efficiency of each treatment process for removal and recovery of phosphorus. This factor was weighted as the scale of 2. It was weighted lower than the previous three factors because while removal and recovery efficiency is a significant consideration, it is not crucial because the assumed swine production facility does not have phosphorus discharge limits. Chemical precipitation can produce phosphorus removal rates of upwards of 90% (Shih et al., 2017), so this treatment method is rated the highest at the scale of 5 for this factor. The processes of adsorption/ion exchange and membrane treatment can also achieve relatively high removal efficiencies as discussed in Sections 2.2.2 and 2.3.2, and therefore are rated highly at the scale of 4. The three biological treatment methods typically have lower phosphorus removal and recovery efficiencies, so they are rated at the scale of 3 or lower for this factor. EBPR and algae utilization can achieve removal rates of up to 78-90% but can vary based on operating conditions and organisms present (Yuan et al., 2012, Abdel-Raouf et al., 2012). Constructed wetlands can typically only reach efficiencies of 30-70% (Shilton et al., 2012).

The fifth factor shown in Table 2 is the process availability. Like the removal efficiency, this factor is not considered critical, so it is weighted lower at the scale of 2. However, treatment processes that are proven and/or commercially available can still be advantageous for a rural facility due to increased resources to assist with operation and maintenance. All the compared processes are common wastewater treatment processes that have been utilized for decades. However, some of the processes have been more widely used for swine wastewater treatment than others. Biological processes such as EBPR, algae utilization, and wetlands have been widely applied for livestock and domestic wastewater treatment and are therefore rated highly. The application of physical/chemical processes such as precipitation, adsorption/ion exchange, and membrane treatment have been researched for phosphorus recovery from swine wastewater in recent years but are less proven than biological processes and are therefore rated lower.

The last factor evaluated for each treatment process is the process footprint. Since the assumed treatment facility has no limitations on land availability for a wastewater treatment process, this factor is weighted the lowest at the scale of 1. The processes for precipitation, adsorption/ion exchange, and membrane treatment for phosphorus removal can be easily integrated into the footprint of a traditional wastewater facility, so these processes are rated highly at the scale of 5. The EBPR process requires a larger footprint than the physical/chemical processes and is rated at the scale of 4. As discussed in Section 3.2.2, algae utilization processes such as an algal pond have a significantly larger footprint than the physical/chemical treatment processes and are therefore rated at the scale of 3 for this factor.

Constructed wetland areas require the largest amount of land and therefore require a large footprint, so this process has a low rating at the scale of 2 for this factor.

As shown in Table 2, the process of algae utilization received the highest total ranking. Therefore, based on the conditions of the assumed swine production facility, algae utilization is the recommended treatment process for phosphorus removal and recovery. A proposed design for the selected treatment process of algae utilization is presented in Section 5.

5. Design of a High Rate Algal Pond System for the Assumed Swine Production Facility

As stated in Section 4, algae utilization is proposed for phosphorus removal and recovery for the assumed swine production facility. Algae utilization is recommended due to its low costs, simple operation and maintenance, and high reuse potential of the recovered phosphorus as fertilizer. This section presents a preliminary design for the algae utilization process in the form of a high rate algal pond. A high rate algal pond was chosen since this type of algae utilization process has less operation and maintenance requirements than a photobioreactor. Additionally, the assumed swine production facility is located in rural South Dakota and has no limitations on land availability making a treatment pond a feasible option.

While there is some research investigating the effectiveness of high rate algal ponds in treating agricultural and domestic wastewater (Sutherland et al., 2014), algal ponds are not typically utilized for high strength wastewater like that in the assumed swine production facility because of concerns such as light transmittance and interactions between algae and heterotrophic bacteria. Additionally, to treat a high strength wastewater an algae pond would require a much larger footprint than other pond types due to the shallow depth. Therefore, a traditional wastewater pond is proposed as a pretreatment step to reduce the BOD and solids loading rate to the high rate algal pond. There are three main types of traditional wastewater treatment ponds including anaerobic, aerobic, and facultative. The typical operating parameters for each type of pond are shown below in Table 3.

Table 3. Basic Wastewater Pond Specifications (USEPA, 2011)

Pond	Application	Typical Loading (BOD_5)*	Typical Detention Time (d)	Typical Depth (m)	Comments
Anaerobic	Industrial wastewater	280-4500 kg / 1000 m^2/d	5-50	2.5-4.5	Subsequent treatment normally required.
Facultative	Raw municipal wastewater. Effluent from primary treatment, trickling filters, aerated ponds, or anaerobic ponds.	22-56 kg/ 1000m^2/d	7-50	0.9-2.4	Most commonly used wastewater treatment pond. May be aerobic through entire depth if lightly loaded.
Aerobic	Generally used to treat effluent from other processes. Produces effluent low in soluble BOD_5 and high in algal solids.	112-225 kg/ 1000 m^2 /d	2-6	0.18-0.3	Maximizes algae production and, if algae are harvested, nutrient removal.

*BOD_5 = Biochemical Oxygen Demand measured over 5 days

Anaerobic ponds operate in an environment that is free of oxygen. The predominant biological treatment reactions in this pond type are bacterial acid formation and methane fermentation (USPEPA, 2011). Anerobic ponds are the deepest type of wastewater pond and can handle the highest BOD loading rates. They are typically utilized for strong wastewaters such as industrial or concentrated agricultural wastewaters (USEPA, 2011) and are particularly effective at BOD removal, which would be advantageous in the case of the assumed swine production facility. However, anaerobic ponds typically produce strong odors. Anaerobic ponds also have a lower organic removal efficiency than facultative or aerobic ponds, and swine wastewater contains hydrogen sulfide which would adversely affect the microbial grown in an anaerobic pond.

Facultative ponds operate as a layered treatment system with an aerobic layer overlaying an anaerobic layer (USEPA, 2011). The aerobic layer provides odor control and some nutrient and

BOD removal, and the anaerobic layer provides the remaining BOD removal and denitrification. Facultative ponds require less depth than anaerobic ponds but applicable BOD loading rates are much lower than both anaerobic and aerobic ponds (USEPA, 2011). Because of the low organic loading rate allowable for facultative ponds, the high strength wastewater from the assumed swine facility would require a pond footprint that is too large to be feasible.

Aerobic ponds (also known as aerated ponds) are operated to maintain dissolved oxygen throughout the pond area and utilize microorganisms to achieve a high degree of BOD removal (USEPA, 2011). These ponds typically have shallower depths than other pond types but can still handle relatively high BOD loading rates, and typically have less odor. If they are not aerated, aerobic ponds must be shallow so that dissolved oxygen can be supplied from the atmosphere. If an aerator is utilized, the pond depth can increase which can reduce the pond footprint. Aerobic ponds do require mixing, which increases their operation costs but typically requires less land area and shorter detention times than other pond types (USEPA, 2011). The assumed swine production facility has a BOD concentration that can be treated by aerobic ponds and an aerobic pond would allow for more effective algae growth and nutrient removal than other pond types as shown in Table 3. Therefore, an aerobic pond is recommended for this facility. A preliminary design for an aerobic pond as a pretreatment step is provided in the following section.

5.1. Aerobic Pretreatment Pond Design

Aerobic ponds can be operated under either partial mix or complete mix aeration conditions, the difference being how much oxygen is introduced into the system. Complete mix ponds rely mechanical aeration to introduce enough oxygen to degrade all BOD and are aerated at a sufficient rate to keep all solids in suspension (USEPA, 2011) and therefore are typically used for wastewater with high BOD concentrations. As stated in Section 4, the wastewater produced by the assumed swine production facility is a high strength wastewater with high BOD. The aerobic pretreatment pond is designed as a completely mixed reactor. It is assumed that in this design, surface aerators would be utilized to keep the solids in the pond aerated and sufficiently mix oxygen throughout the wastewater. However, the design of the aeration system is not within the scope of this study and is not evaluated.

The complete mix model for the aerated pond design utilizes the first order kinetics and is dependent upon the number of equal sized cells operating in series (USEPA, 2011). Increasing the number of cells in a completely mixed pond creates a flow behavior that is closer to a plug flow reactor, which increases the treatment efficiency. In this design method, the known influent BOD concentration and desired effluent BOD concentration are used to calculate the required hydraulic detention time. The calculated hydraulic detention time is then used to calculate the required pond size. The complete mix model is shown below in Equation 1 (USEPA, 2011).

Complete Mix Model

$$\frac{C_n}{C_o} = \left(\frac{1}{1+k_c t_n}\right)^n \qquad t = \frac{n}{k}\left[\left(\frac{C_o}{C_n}\right)^{\frac{1}{n}} - 1\right] \tag{1}$$

Where:

C_n = effluent BOD_5 concentration in cell n, mg/L
C_o = influent BOD_5 concentration, mg/L
k = first order reaction rate constant /d
t = total hydraulic residence time in pond system, d
n = number of cells in the series

In this equation, the pond influent BOD_5 concentration (C_o) is equivalent to the BOD_5 concentration of 36,304 mg/L from the assumed swine production facility. The pond effluent concentration (C_n) is set at a level that is an acceptable influent quality for the high rate algal pond downstream of the aerobic pretreatment pond. High rate algal ponds can typically efficiently treat domestic wastewater without pretreatment (Couto et al., 2021) and therefore the C_n value was set as 300 mg/L BOD_5, which is typical in domestic wastewaters.

The remaining constant value in the complete mix model equation is the first order reaction rate constant (k). The reaction rate constant can vary by wastewater type. Ndegwa et al. (2007) reported that swine manure has a decay rate of 0.164/day. The 10 States Standards for Wastewater Facilities (2014) recommends a k value of 0.12/day at 20°C for domestic wastewater. To be conservative pond in the design, the k value of 0.12/day is used. The average annual temperature for eastern South Dakota is approximately 5°C (U.S. Climate Data, 2022). Therefore, the reaction rate constant is corrected for temperature using Equation 2. For this equation, it is assumed that the temperature of pond water (T_w) is 5°C. After being corrected for temperature, the k value used in Equation 1 was 0.067/d.

Temperature Effects

$$k_T = k_{20}\theta^{T_w - 20} \tag{2}$$

Where:

k_T = reaction rate at temperature T/d
k_{20} = reaction rate at 20° C/d
θ = temperature coefficient = 1.036
T_w = temperature of pond water, °C

To determine the required hydraulic residence time (t) for the aerobic pond to treat the wastewater to the desired BOD_5 effluent concentration, the number of pond cells (n) of 4 is used. Using C_o = 36,304 mg/L, C_n = 300 mg/L, k = 0.067/d, and n = 4, a t value of approximately 140 days was calculated. The calculated t value of 140 days was then multiplied by a flow of 328 ft^3/d to calculate the required pond volume. Section 4 describes the method for calculating the pond's daily influent flow of 328 ft^3/d.

To determine the final pond dimensions, the calculated pond volume was used to determine the pond depth and surface area. The values of depth and surface area were calculated iteratively to determine the ideal dimensions based on the required loading rate. As shown in Table 3, the maximum loading rate for BOD_5 that is typically allowed for aerated ponds is 225 kg/1000 m^2/d (USEPA, 2011). Pond loading rate is based on the influent BOD_5 concentration, pond surface area, and incoming flow. Pond conditions of a daily influent flow of 328 ft^3/d, surface area of 15,200 ft^2, depth of 3.0 ft, and influent BOD_5 concentration of 36,304 mg/L would result in a loading rate of approximately 223 kg/1000 m^2/d, which is within the allowable range. A length to width ratio of 4 was assumed to calculate the final pond dimensions. The final aerobic pond design determined a 250 ft long pond with a width of 65 ft and a depth of 3 ft. The pond would operate as a series of 4 cells, each with a width of 16.25 ft. A schematic of the aerobic pond design is shown in Figure 9. Full design calculations are shown in Appendix A.

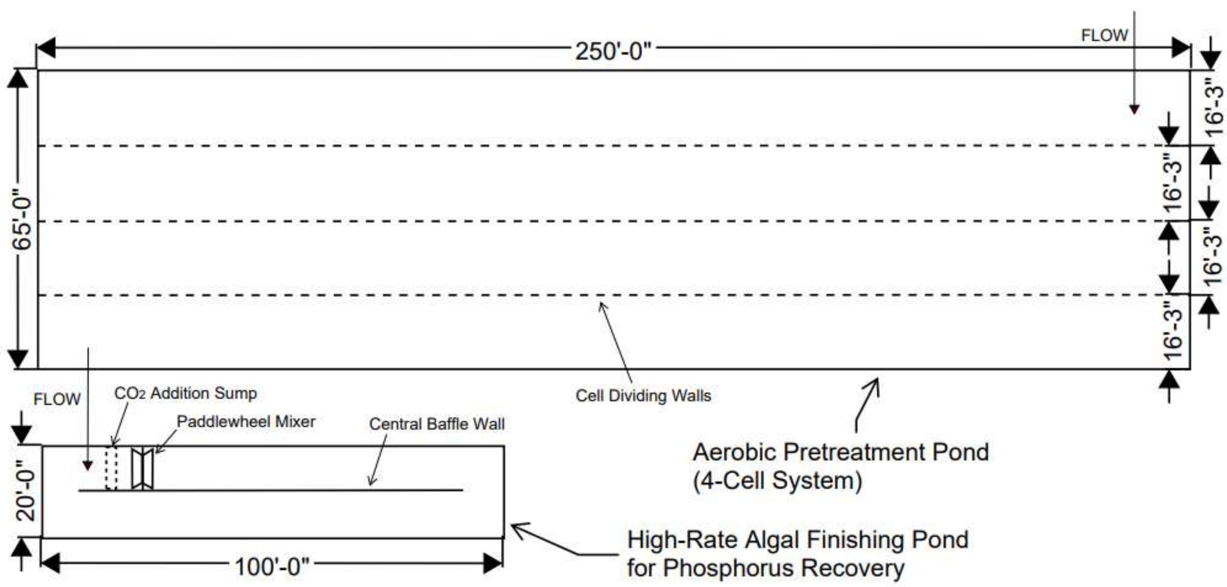

Figure 9. Pond Design Schematic

5.2. High Rate Algal Pond Design

The design of high rate algal ponds is based on the hydraulic retention time and pond depth and does not typically consider a design loading rate. High rate algal ponds require less depth and shorter retention times than typical wastewater ponds, with a recommended hydraulic retention time of between 4 and 10 days and a recommended pond depth of 300-500 mm (LGASA, 2020). Some studies have shown that algae productivity and nutrient removal efficiency improve in the high rate algal pond as the depth increases (Sutherland et. al., 2014). Therefore, the depth of 500 mm (1.64 ft) was chosen for this design to maximize the phosphorus recovery potential of the pond. The hydraulic retention time of 10 days was chosen in the interest of maintaining a conservative design based on the nature of the agricultural wastewater from the assumed swine production facility.

To determine the required dimensions for the high rate algal pond, the hydraulic detention time of 10 days was multiplied by a flow of 328 ft^3/d to calculate the required pond volume. Section 4 describes the method for calculating the pond's daily influent flow of 328 ft^3/d. The required pond volume was determined to be approximately 3,280 ft^3. This value was divided by the chosen pond depth of 1.64 ft to calculate the pond surface area. The calculated pond surface area was approximately 2,000 ft^2. A length to width ratio of 5 was assumed to calculate the final pond dimensions. The final pond design determined a 100 ft long pond with a width of 20 ft and a depth of 1.64 ft. A schematic of the high rate algal pond design is shown in Figure 9. Full design calculations are shown in Appendix A.

Further design considerations for the high rate algal pond include the pond's configuration and requirements for mixing and carbon dioxide addition. As described in Section 3.2.1, high rate algal ponds are typically configured with baffles to form a raceway flow pattern and include paddlewheel mixers to mix the influent with the rest of the wastewater flow and to maintain a constant flow velocity (LGASA, 2020). Additionally, carbon dioxide (CO_2) is added to the wastewater flow to control the pH in the pond and provide a sufficient carbon source for algae growth (Couto et al., 2021). While these factors are important for efficient phosphorus removal and recovery from the high rate algal pond, they are not within the scope of this study and are not evaluated. For this design scenario, it is assumed that the high rate algal pond has sufficient mixing and carbon dioxide addition, and these components are included in Figure 9.

6. Conclusions

The removal of phosphorus from wastewater is an important consideration in treatment processes because of the harmful effects of phosphorus in wastewater effluent on the environment. It is also a significant area of interest due to the possibility of the reuse potential of this nutrient as a resource. In this study, six wastewater treatment methods for phosphorus removal and recovery were compared and evaluated based on their applicability for small, rural facilities treating livestock wastewater. These methods included chemical precipitation, adsorption and ion exchange, membrane processes, enhanced biological phosphorus removal (EBPR), constructed wetlands, and algae utilization. These methods were then evaluated based on six factors to decide which would be recommended for the assumed swine production facility. This evaluation can provide an example for determining the applicability for similar facilities. The recommended treatment process for the assumed facility was algae utilization and a proposed design for a high rate algal pond was presented.

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APPENDIX A

Design Calculations

Assumed Conditions of the Assumed Swine Production Facility

- Swine production facility housing 100 finisher pigs
- Typical weight range for finisher pigs = 60-250 lbs (USEPA, 2004)
- Typical manure generation rate for swine facilities = 132 lb/day per 1000lb animal weight (USEPA, 2004)
- Annual Average Temperature = 40°F = 5°C

Assumed Swine Wastewater Conditions

- Aerobic pond influent BOD_5 concentration = 36,304 mg/L
- Aerobic pond effluent BOD_5 concentration = 300 mg/L
- Wastewater reaction rate constant = 0.12/d at 20°C (10 States Standards, 2014)
- High rate algal pond required hydraulic retention time = 10 days
- High rate algal pond required depth = 1.64 ft

Calculated Conditions of the Assumed Swine Production Facility

- Average Weight Per Animal

$$Weight_{Avg}\ (lb) = \frac{(60 + 250)}{2} = 155\ lb$$

- Total Animal Weight in Facility

$$Weight_{Total}\ (lb) = (155\ lb/animal)(1000\ animals) = 155{,}000\ lb$$

- Total Manure Generation Rate for Facility

$$Generation\ Rate\ (lb/d) = \ (Weight_{Total}\ (lb))\left(\frac{132\,\frac{lb}{d}}{1000\ lb\ weight}\right)$$

$$= (155{,}000\ lb)\left(\frac{132\,\frac{lb}{d}}{1000\ lb\ weight}\right) = 20{,}460\ lb/d$$

- Total Daily Wastewater Flow for Facility

$$Flow\ (ft^3/d) = \ (Weight_{Total}\ (lb))\left(\frac{1\ ft^3\ H_2O}{62.4\ lb\ H_2O}\right) = (20{,}460\ lb/d)\left(\frac{1\ ft^3}{62.4\ lb}\right)$$

$$= 327.9\ \ ft^3/d$$

- Wastewater Quality Parameter Conversion

$$C\ (mg/L) = (X\ (lb/d))\left(\frac{1\ d}{2.12\ ft^3}\right)\left(\frac{454\ g}{1\ lb}\right)\left(\frac{35.315\ ft^3}{1\ m^3}\right)\left(\frac{1\ m^3}{1000\ L}\right)\left(\frac{1000\ mg}{1\ g}\right)$$

Design of Aerobic Pond

1) Determine required hydraulic retention time:

Aerobic pond design is based on EPA Complete Mix Model Equation (USEPA, 2011).

$$\frac{C_n}{C_o} = \left(\frac{1}{1+\ k_c t_n}\right)^n \ or\ t = \frac{n}{k}\left[\left(\frac{C_n}{C_o}\right)^{\frac{1}{n}} - 1\right]$$

Where:

- C_n = Effluent BOD_5 concentration = 300 mg/L
- C_o = Influent BOD_5 concentration = 30,000 mg/L
- k = Reaction rate constant = 0.12/d at 20°C
- n = number of cells = 4
- t = hydraulic residence time in pond system (d)

Temperature Correction Equation:

$$k_T = \ k_{20}\theta^{Tw-20}$$

Where:

- k_T = reaction rate at temperature T
- k_{20} = reaction rate at 20°C = 0.12/d
- θ = temperature coefficient = 1.036
- T_W = temperature of pond water in °C

$$k_T = (0.12)(1.036)^{(5-20)} = 0.067/d\ \ at\ 5°\mathrm{C}$$

Therefore:

$$t = \frac{4}{\frac{0.067}{d}}\left[\left(\frac{36{,}304\,\frac{mg}{L}}{300\,\frac{mg}{L}}\right)^{\frac{1}{4}} - 1\right] = 139.1\ days$$

2) Determine Required Pond Dimensions:

Required pond volume is based on daily wastewater flow and hydraulic retention time:

$$Volume\ (ft^3) = (Total\ Flow)(t)$$

$$V = (327.9\ \ ft^3/d)(139.1\ days) =\ 45{,}601\ ft^3$$

Assume aerobic pond depth of 3 ft:

$$Surface\ Area\ (ft^2) = \frac{Volume\ (ft^3)}{Depth\ (ft)}$$

$$A = \frac{45{,}601\ ft^3}{3\ ft} = 15{,}200\ ft^2$$

Assume length to width ratio (L:W) of 4:

$$A\ (ft^2) = (L\ (ft))(W\ (ft)) = (4W)(W) = 4W^2$$

$$W\ (ft) = \sqrt{\frac{A(ft^2)}{4}} = \sqrt{\frac{15{,}200\ ft^2}{4}} = 61.6\ ft$$

$$L\ (ft) = 4\big(W\ (ft)\big) = 4(61.6\ ft) = 246.6\ ft$$

To maintain a conservative design, pond dimensions are rounded up to the next 5-foot increment, Therefore, the final aerobic pond design consists of a pond with the following dimensions:

- Length = 250 ft
- Width = 65 ft
- Depth = 3 ft
- Number of Cells = 4
- Width per Cell = 16.25 ft

3) Check Aerobic Pond Organic Loading Rate:

Maximum organic loading rate typically allowed for aerobic ponds is 225 kg/1000 m^2/d (USEPA, 2011).

Determine pond loading rate based on final design dimensions, design flow, and influent BOD_5 concentration:

$$A\ (ft^2) = \big(L\ (ft)\big)\big(W\ (ft)\big) = (250\ ft)(65\ ft) = 16{,}250\ ft^2$$

$$A\ (m^2) = (16{,}250\ ft^2)\left(\frac{1\ m^2}{10.764\ ft^2}\right) = 1{,}510\ m^2$$

$$Design\ Flow\ (L) = (327.9\ \ ft^3/d)\left(\frac{28.317\ L}{1\ ft^3}\right) = 9{,}285\ L/d$$

$$Pond\ Organic\ Loading\ Rate\ (mg/m^2/d) = \frac{\left(\text{Influent BOD}_5\text{ concentration }\left(\frac{\text{mg}}{\text{L}}\right)\right)\left(Flow\ \left(\frac{L}{d}\right)\right)}{Pond\ Area\ (m^2)}$$

$$Pond\ Organic\ Loading\ Rate\ = \frac{\left(36{,}304\ \frac{\text{mg}}{\text{L}}\right)\left(9{,}285\ \frac{L}{d}\right)}{1{,}510\ m^2} = 223{,}234\ mg/m^2/d$$
$$= 223\ kg/1000\ m^2/d$$

Comparison:

$$223\ kg/1000\ m^2/d\ <\ 225\ kg/1000\ m^2/d$$

Therefore, the pond organic loading rate is acceptable for the designed aerobic wastewater treatment pond.

Design of High Rate Algal Pond

- High rate algal pond required hydraulic retention time (t) = 10 days
- High rate algal pond required depth = 1.64 ft

1) Determine Required Pond Dimensions:

Required pond volume is based on daily wastewater flow and hydraulic retention time:

$$Volume\ (ft^3) = (Total\ Flow)(t)$$

$$V = (327.9\ ft^3/d)(10\ days) = \ 3{,}279\ ft^3$$

Assume high rate algal pond depth of 1.64 ft:

$$Surface\ Area\ (ft^2) = \frac{Volume\ (ft^3)}{Depth\ (ft)}$$

$$A = \frac{3{,}279\ ft^3}{1.64\ ft} = 2{,}000\ ft^2$$

Assume length to width ratio (L:W) of 5:

$$A\ (ft^2) = (L\ (ft))(W\ (ft)) = (5W)(W) = 5W^2$$

$$W\ (ft) = \sqrt{\frac{A(ft^2)}{5}} = \sqrt{\frac{2{,}000\ ft^2}{5}} = 20.0\ ft$$

$$L\ (ft) = 5\big(W\ (ft)\big) = 4(20.0\ ft) = 100\ ft$$

Therefore, the final high rate algal pond design consists of a pond with the following dimensions:

- Length = 100 ft
- Width = 20 ft
- Depth = 1.64 ft