Mother Road Brewing Company
Final Design Report

CENE 486C

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To: Michael Marquess, CEO
Mother Road Brewing Company

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List of Abbreviations

AOPs	Advanced Oxidative Processes
BOD	Biological Oxygen Demand
COC	Contaminants of Concern
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
DAF	Dissolved Air Flotation
EF-SBR	Electro-Fenton Sequential Batch Reactor
EIT	Engineer-in-Training
FBMBR	Hybrid Fixed Bed Membrane Bioreactor
HRT	Hydraulic Retention Time
IBE	Inner Basin Environmental
LAB	Lab Technician
MLSS	Mixed Liquor Suspended Solids
MRBC	Mother Road Brewing Company
NAU	Northern Arizona University
NF	Nanofiltration
PE	Project Engineer
RO	Reverse Osmosis
SE	Senior Engineer
SM	Standard Method
SRT	Solids Retention Time
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
USABs	Upflow Anaerobic Sludge Blankets
VSS	Volatile Suspended Solids
WWTP	Wastewater Treatment Plant

Acknowledgements

The team would like to thank Dr. Diana Calvo Martinez for her contributions in researching the effects on BOD, TSS, and TKN in wastewater. Her effort to teach the team about contaminant of concern effects on the wastewater treatment plan in addition to providing necessary equations for half reactions and modeling does not go unnoticed. In addition, as a technical advisor, Dr. Calvo Martinez has assisted the team in obtaining professional advice and guidance from her colleagues throughout the course of the project.

In addition, the team at Mother Road Brewing Company has assisted the Still Water Treatment Engineering team by answering pertinent questions in a timely manner, allowing the team access to the facility, and providing weekly lab data.

1.0 Project Understanding

1.1 Project Name

Mother Road Brewing Company (MRBC) Pre-treatment.

1.2 Project Location

The MRBC's Butler Brewing facility is located at 1300 E Butler Ave. in Flagstaff, AZ. Figure 1-1 shows the MRBC Butler Brewery in Flagstaff where Figure 1-2 shows MRBC's Butler Brewery location in reference to the local area.

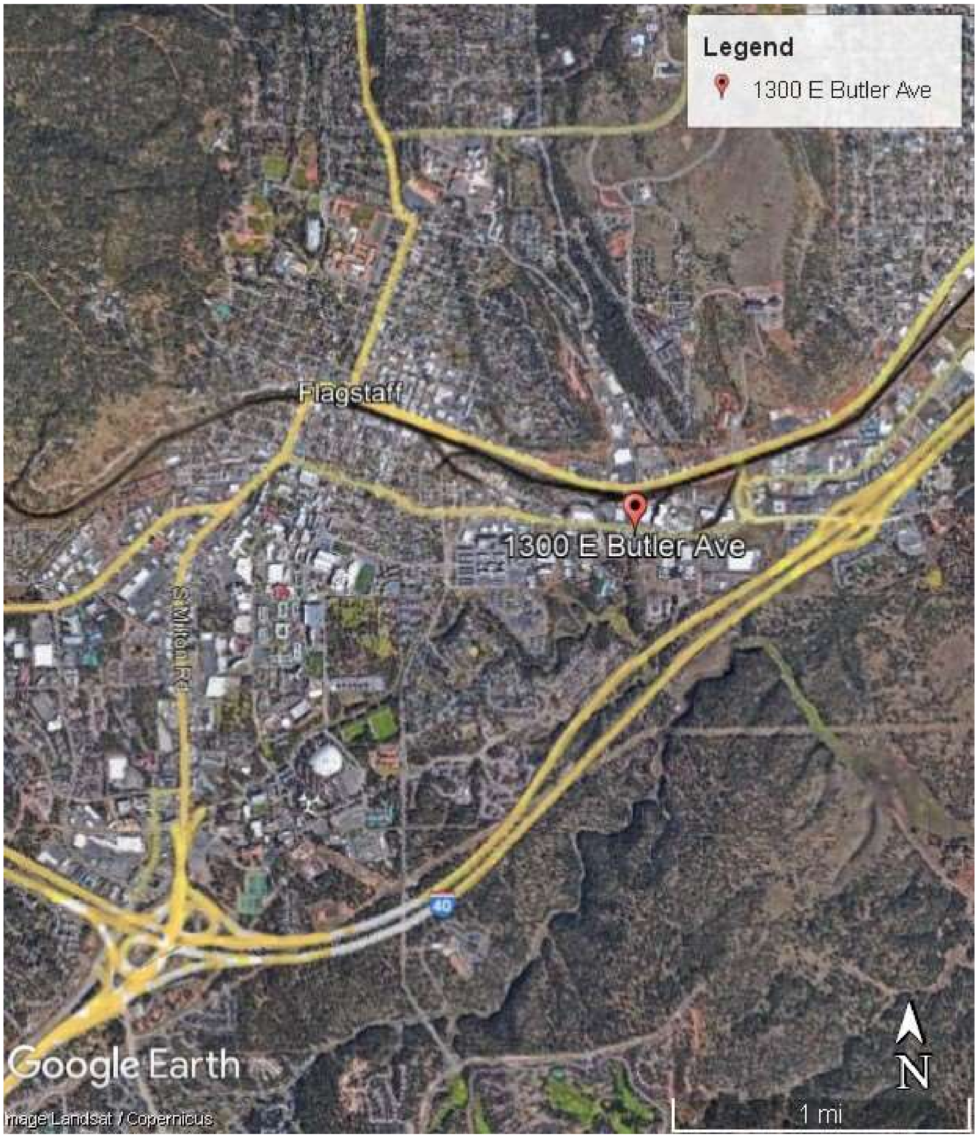

Figure 1-1: MRBC's Butler Brewing Facility in Flagstaff, AZ [1]

Figure 1-2: MRBC's Butler Brewing Facility in the Local Area [1]

1.3 Project Purpose and Current Conditions

The purpose of this project is to reduce contaminant of concern (COC) concentrations in Mother Road Brewing Company's wastewater effluent. The specified project COCs are Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), and Total Kjeldahl Nitrogen (TKN). Among these COCs, BOD is the most concerning; TKN concentrations are currently trending upwards. High concentrations of all COCs have the potential to disturb the wastewater treatment process at the Rio De Flag Treatment Plant due to the delicate nature of the wastewater treatment process. Exceeding local wastewater regulatory codes has resulted in the City of Flagstaff fining MRBC for each month that exceedances occur. Meeting local standards will prevent financial losses and allow for future process improvements. Furthermore, increasing the environmental sustainability of the brewery's procedures by reducing COC levels may additionally influence local breweries to adopt a higher standard for their production practices.

In addition, the client has communicated that MRBC intends to grow significantly within the next 10 years. However, this growth cannot be quantified. For this reason, the client has two requests with respect to the pretreatment unit's capacity. One is that the unit must be designed for their current maximum wastewater production volume at approximately 8,125 gallons per day. Additionally, the unit must be developed considering that MRBC may construct additional units according to their needs. Designing a pretreatment unit that is easily replicated and can be implemented as an independent unit or multiple units in configuration will therefore be a challenge to the design team.

Measurements for contaminant levels are being recorded once a week at the MRBC Butler facility with testing being conducted by Inner Basin Environmental (IBE) Labs in Flagstaff, Arizona. MRBC's maximum wastewater discharge flow rate is 8,125 gallons/day and is used as the design flow rate. Ranges of contaminant levels from August 2022 to February 2023 and their respective test methods are shown in Table 1-1. The City of Flagstaff permit limits are shown in Table 1-2. Using a design flow rate of 8,125 gallons/day, the BOD and TSS permit limits were converted to mg/L (values in Table 1-1). Sample calculations showing the conversions can be found in Appendix A. Samples are collected and tested on a weekly basis and are tested according to the test method listed in the table below.

Table 1-1: COC Concentration Ranges, 2022-2023

Contaminant	**Current Concentration (mg/L)**	**Standards for Discharge** [2] **(mg/L)**	**Test Method**
BOD	3,108 – 21,075	10,323*	Standard Method (SM) 5210 B
TSS	120 – 1,860	1,917*	Standard Method (SM) 2540 C
TKN	104 –211	173	EPA 351.2

*This value changes based on the discharge flow rate [2].
Yellow: Concentration is in exceedance

Figures 1-3 through 1-5 display the concentration ranges of BOD, TSS, and TKN over time with the discharge permit limits shown in orange:

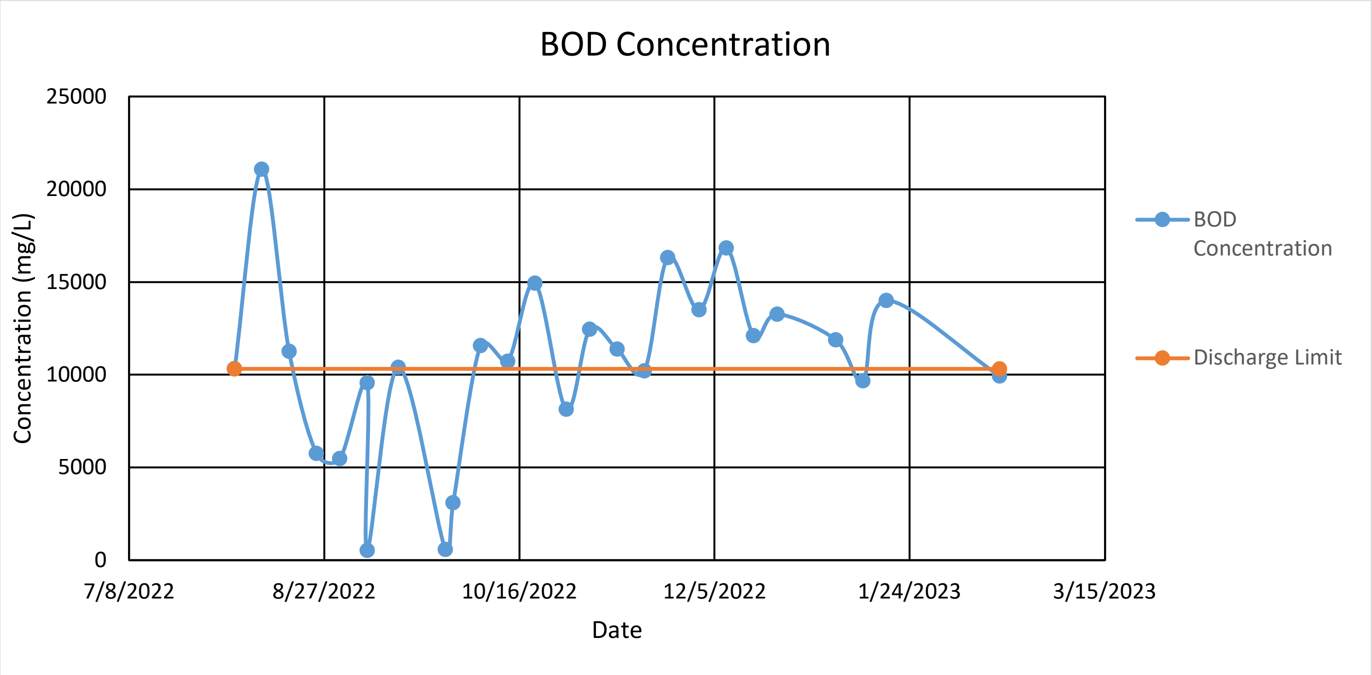

Figure 1-3: BOD Concentration Over Time

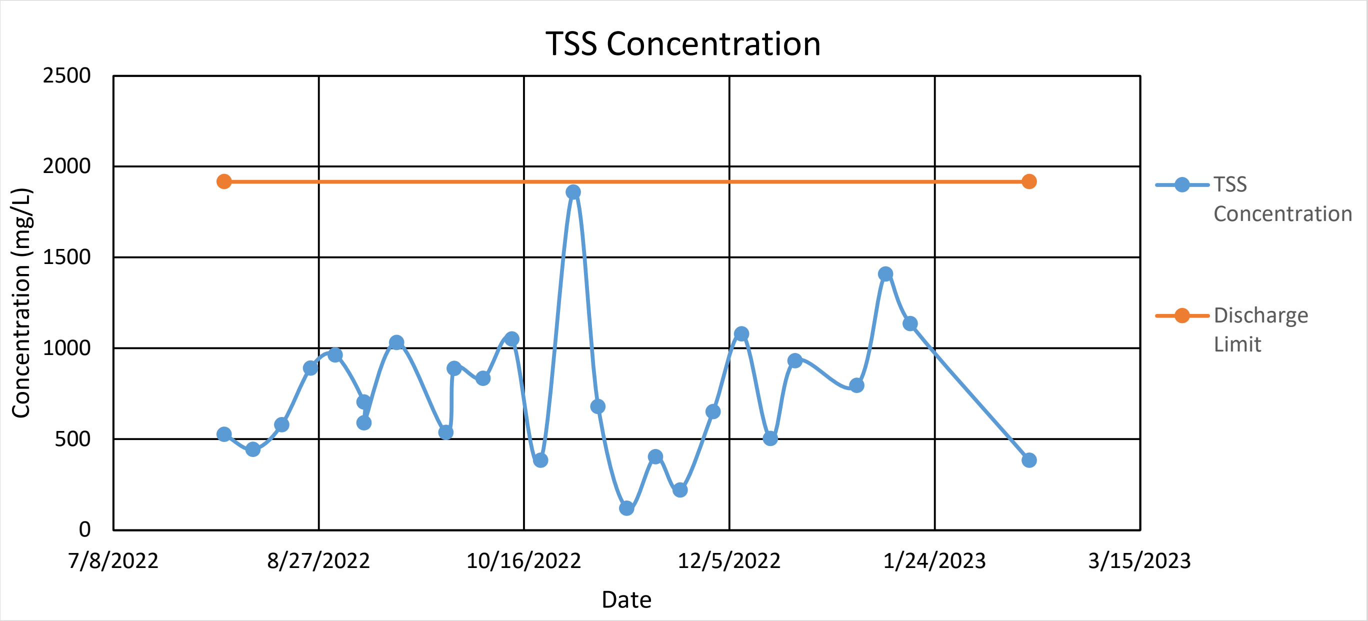

Figure 1-4: TSS Concentration Over Time

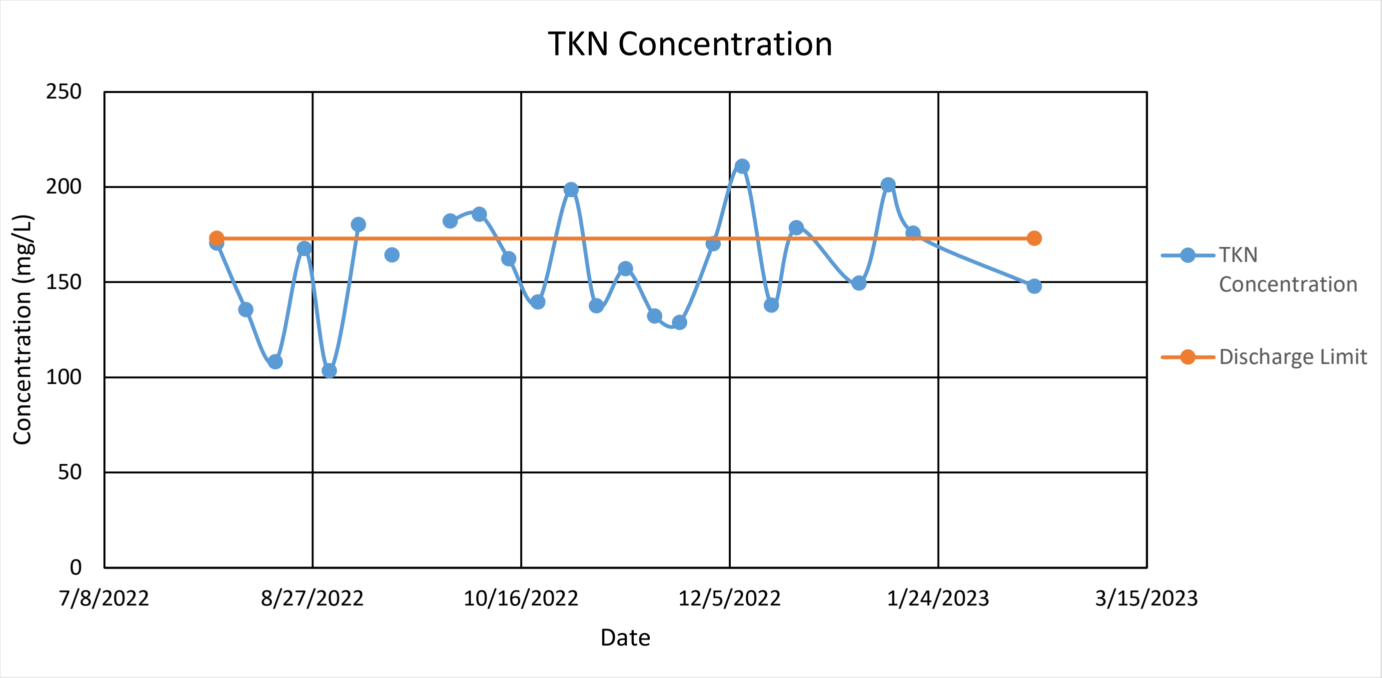

Figure 1-5: TKN Concentration Over Time

The graphs above show the variability of each COC concentration over time. Since MRBC brews different beers daily with varied ingredients and at different levels of production, there is a strong variance in these data sets.

The actual City of Flagstaff permit standards are shown in Table 1-2:

Table 1-2: Flagstaff City Code Standards for Discharge [2]

Contaminant of Concern	Standard for Discharge	Units
BOD	700	lb/day
TSS	130	lb/day
TKN	173	mg/L

As identified in Table 1-1, BOD and TKN are the main COCs for the project since those current concentrations are in exceedance in comparison to the standards in Flagstaff City Code, *Chapter 7-02: Wastewater Regulations,* 7-02-001-0008 [2].

1.4 Project Constraints

The project was constrained by the available space for the selected design alternative. Space was limited to an 8' x 20' shipping container size per the client's request; therefore, the design must have been compact so that it fit within the designated limits. In addition, the client also requested that the design be placed outside of the building, so the chosen design must be able to handle extreme weather conditions.

Another constraint was budget for the design. The budget was determined using an 18-month return on investment based on the additional monthly fine by the City of Flagstaff of $24,000/month. Thus, the estimated budget for the project was $432,000.

The final design was not physically constructed due to time and budget limitations. Instead, each alternative was modeled using Excel with modeling equations.

2.0 Preliminary Research

2.1 Existing MRBC Process

The design team developed a block diagram to describe the MRBC production processes, including the washing cycles. Figure 2-1 below shows the process.

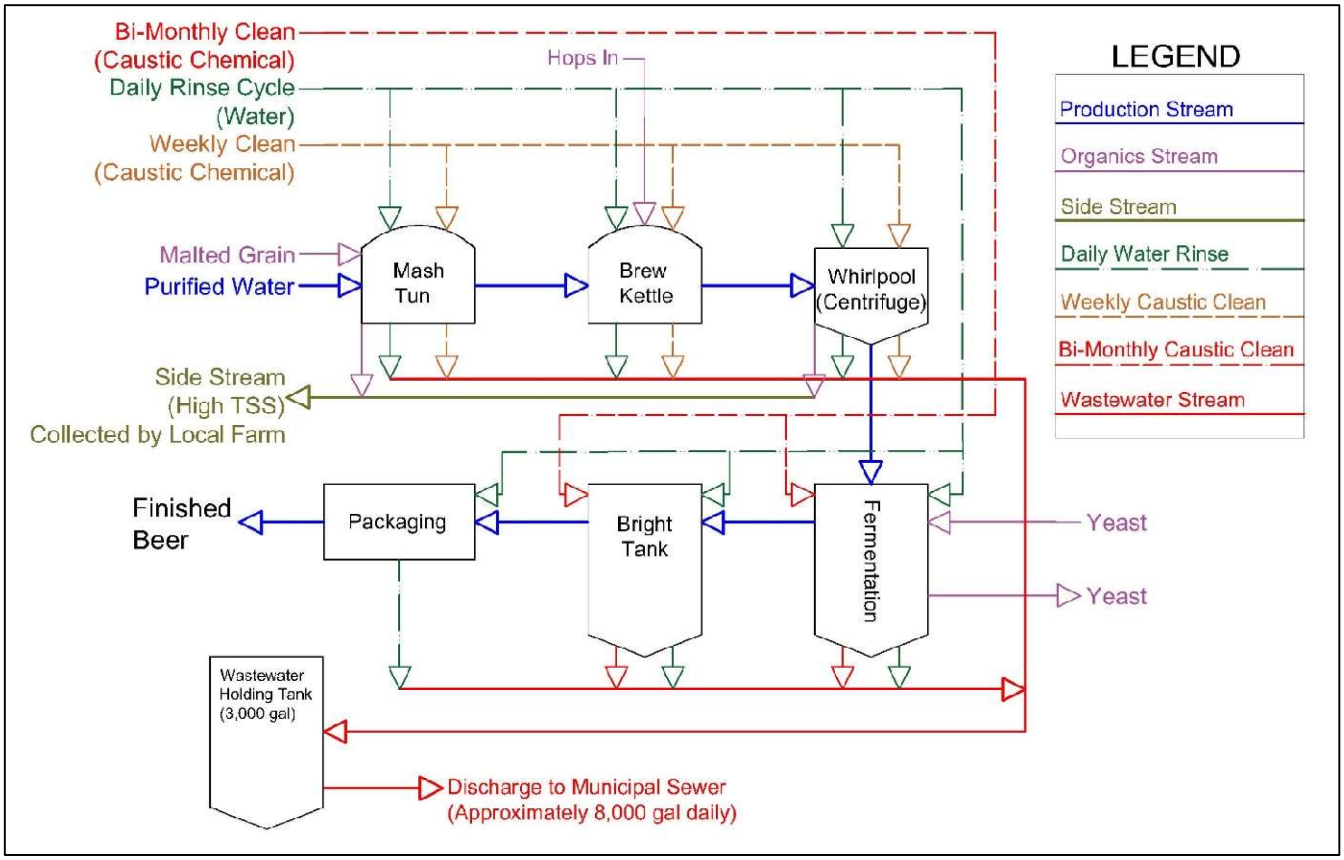

Figure 2-1: MRBC Process Flow Block Diagram

The brewing process begins with adding purified water and a roasted malt to the mash tun. Added malt has undergone a roasting process prior to addition that has cracked open the kernel's husk, exposing the starch within. This mixture is heated between 100-170 degrees Fahrenheit, a process known as mashing. Temperature and duration are selected according to the brewer's recipe. The mashing process activates enzymes which convert the malt's starches into proteins and fermentable sugars [3]. The solution of sugars, proteins, and water is called wort.

Once the brewer is satisfied with the wort, the solution is allowed to settle. Malted grain that has settled to the bottom of the mash tun is then used to filter the wort as it is drained. The brewer may recirculate the drained word back through the settled grain to further filter out solids. Once the brewer is satisfied with the clarity of the wort it proceeds into the brew kettle [3]. For MRBC, malted grain that remains within the mash tun is removed and collected by a local farm to feed livestock. Once in the brew kettle, the wort is boiled, stopping enzymatic reactions [3]. Hops are added to the wort during this step. Hops are selected according to the brewer's recipe and may be added at different times to affect flavor [3].

Upon completion of boiling, the wort moves into a whirlpool (centrifuge) for clarification. The whirlpool spins the wort and separates solids through settling. The separated solids (slurry), called turb, contains proteins, hops, and any other residual solids that remain after brewing [3]. This slurry is discharged and collected by a local farm to fertilize crops. As the wort leaves the whirlpool, MRBC cools the solution so that it may be at the proper temperature to continue into fermentation.

Once within fermentation tanks, yeast is added to the wort to metabolize sugars into alcohol and carbon dioxide [3]. Different variables affect fermentation such as type and amount of yeast, temperature of the solution, and detention time of the yeast [3]. MRBC normally ferments their beers from 14 to 16 days.

Once fermentation is complete, yeast is collected to be recycled or disposed of. Fermented beer then continues into a bright tank. As beer enters the bright tank, it is cooled to near freezing temperatures. This cooling of beer stops fermentation and is known as cold crashing. Beer will remain in the bright tank under cold storage until the beer has matured. Here MRBC brewers carefully monitor the beer to ensure the finished flavor is consistent. Once the targeted flavor has been achieved, the finished beer continues to packaging where it may be kegged or canned, finishing the product.

Each stage of the brewing process produces a varying amount of wastewater. The volume of wastewater streams varies according to production volume and type of beer. MRBC conducts a water rinse and a caustic clean which varies in frequency according to the object being cleaned. Objects in MRBC’s brewhouse (mash tun, brew kettle, whirlpool) undergo a waste rinse after each use cycle, and a weekly caustic clean. Objects in MRBC’s cellar (fermentation and bright tanks) undergo a water rinse after each use cycle and a caustic clean approximately twice monthly. All wastewater streams are collected in a 3,000-gallon wastewater holding tank. Once this holding tank reaches capacity it is then discharged directly into the municipal sewer. Each discharge occurs when the holding tank is expected to overflow. Therefore, the total average daily wastewater discharge from MRBC into the municipal sewer is approximately 8,125 gallons per day.

2.2 Effects of BOD, TKN, and TSS on Wastewater

A wastewater treatment plant sets pre-treatment standards to prevent their system from becoming overloaded. An overloading of the system could result in the treatment plant discharging untreated water or may permanently damage the system. This damage would primarily result from a death event of the microbiological population in the system which is caused by high concentrations of contaminants. If the treatment system were to experience damage, treatment would become ineffective and would cause the plant to shut down. This instance would be expensive for the treatment plant and would prove detrimental to the local community's ability to treat high quantities of incoming wastewater.

In terms of the specified contaminants for the project, BOD is a hazard to the microbial community as it consumes the oxygen that the aerobic bacteria used at many treatment plants require to survive. When microbes are starved of oxygen, the system becomes anaerobic and begins to generate more sludge. This not only interferes with treatment and incurs higher maintenance costs, but can also cause the sludge to accumulate beyond the treatment plant's maximum design limits.

TSS in high concentrations is a concern for many of the same reasons as BOD. High TSS concentrations interfere with oxygen uptake and suffocates the microbes. Additionally, the suspended solids may become entrained and may clog the system.

TKN in high concentrations creates a toxic environment and thus also kills the microbes. Much like the other two contaminants, this is a concern to the plant because it can be difficult to recover from and interferes with the treatment system.

2.3 Biological Reactions

Interactions occurring via biological treatment are represented by half reactions. Half reactions are utilized in a method that produces a general reaction. The method of forming a general reaction from half reactions span according to wastewater constituents. Variances differ according to the wastewater's electron donor, electron acceptor, and cell-synthesis half reactions. The general equation developed from half reactions shall communicate consumption and production of materials within the treatment system.

Research has been conducted to identify the appropriate half reactions according to MRBC's wastewater. These half reactions and the method of utilizing them to create a general equation will be detailed within Section 5.

2.4 Pretreatment Methods and Designs

Considering the immediate need to reduce BOD and TKN concentration levels, pretreatment technologies have been researched according to the reduction efficiencies of each COC. Table 2-1 shows the pre-treatment technologies evaluated. An "X" indicates that the method can remove that contaminant. Each technology is discussed below the table.

Table 2-1: Pre-Treatment Technologies and Contaminant Applicability

Technology	**BOD**	**COD**	**TKN**	**TSS**	**Phosphorus**
Dissolved Air Floatation	X	X		X	
Upflow Anaerobic Sludge Blanket (Anammox)	X	X	X	X	
Membrane Filtration	X	X		X	
Microalgae Treatment			X		X
Electro-Fenton Sequential Batch Reactor			X		
LEAPmbr™			X		
Continuously Stirred Tank Reactor	X	X	X		
Hybrid Fixed Bed Membrane Bioreactor	X		X	X	
Settling Tank	X			X	
Trickling Filter	X	X	X		X
Aerobic Sequencing Batch Reactor	X	X			

It should be noted that there are many more treatment technologies that are not mentioned in this analysis. Treatment solutions that use lagoons or large areas for treatment were not considered for this project due to the size constraint. Technologies that do not reduce either BOD or TKN are also not mentioned in the descriptions below due to their inability to complete the project goal of reducing COCs to acceptable levels.

2.4.1 Dissolved Air Floatation

Dissolved air flotation (DAF) is an anerobic method for reducing BOD, COD, and TSS levels in wastewater. Dissolved air flotation is the process of microbubbles attaching to flocculated particles and suspended solids, causing them to float to the surface to be skimmed off [4]. Because BOD and COD are often sorbed onto suspended solids, BOD and COD can be reduced by 50% while TSS is reduced by 99% [5]. In addition, DAF technologies are not very susceptible to changes in temperature, operate at atmospheric pressure, don't require a lot of pressure/energy, are highly efficient, and do not require a long start-up time [4]. Additionally, these systems are inexpensive to install and maintain, but are not considered the best solution to reduce BOD in wastewater treatment plants. An illustration of this technology has been provided in Figure 2-2.

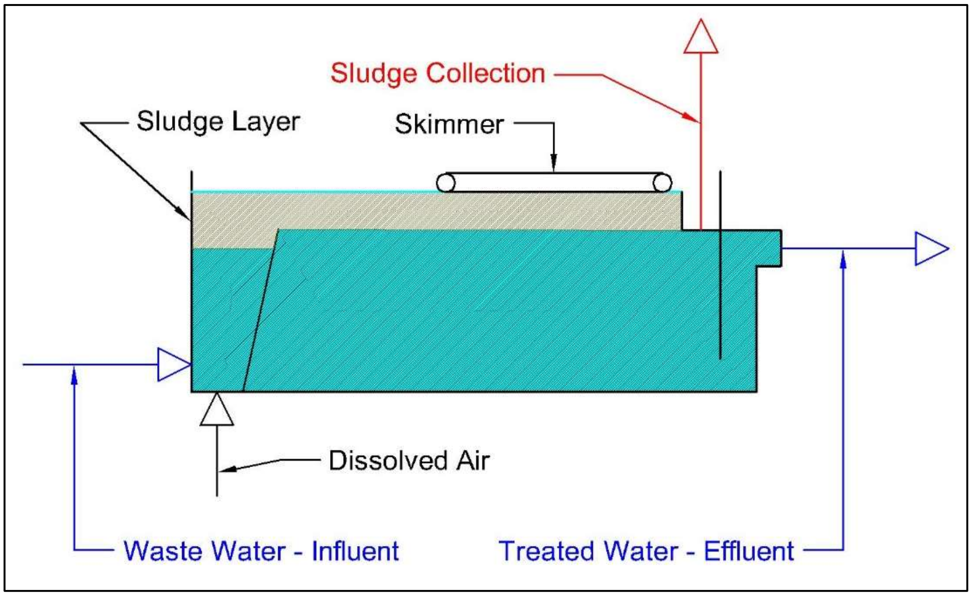

Figure 2-2: Dissolved Air Floatation Block Diagram

2.4.2 Upflow Anaerobic Sludge Blanket

Upflow anaerobic sludge blankets (UASBs) enhanced with anerobic ammonium oxidation (Anammox) bacteria is an ideal treatment solution for reducing BOD, and COD, TSS, and TKN. These systems use anaerobic bacteria to breakdown organics in the absence of oxygen. In addition to producing treated effluent, USABs produce a biogas mixture as a byproduct resulting from anerobic conditions [6]. Methane and carbon dioxide are constituents of this biogas mixture. As such, this byproduct may be captured to provide an energy source to run the system if biogas production volumes are sufficient and properly collected.

UASBs function by passing organic rich wastewater through a sludge blanket located within the treatment unit. A separator located at the top of the unit settles solids, collects biogas, and allows treated wastewater to overflow for collection [6]. This process has been illustrated below in Figure 2-3.

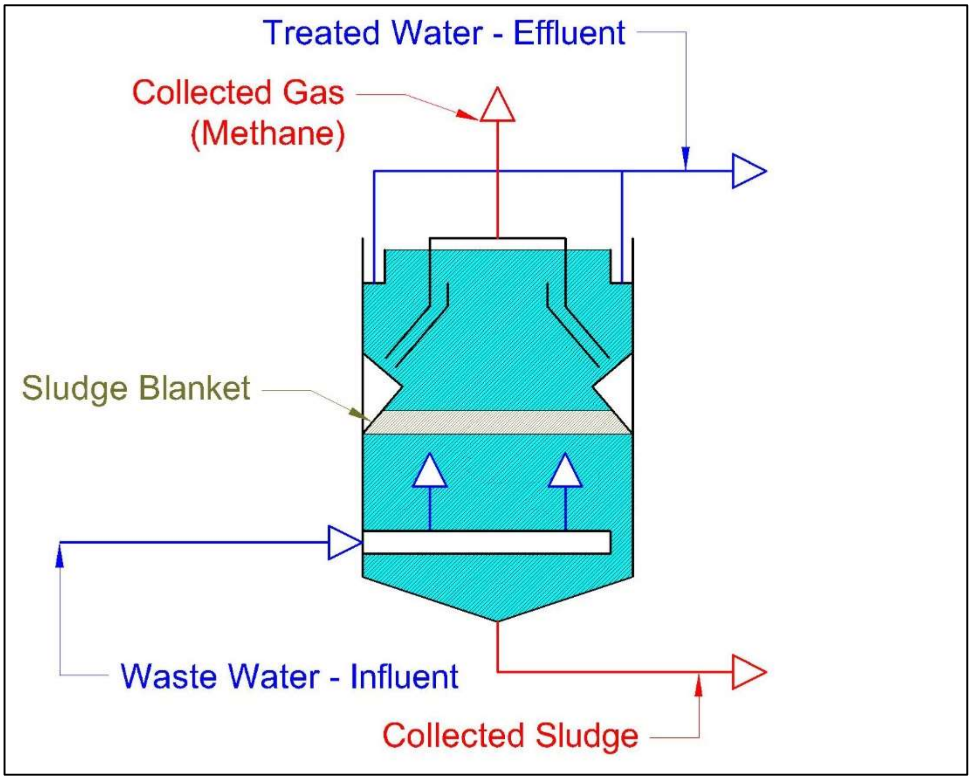

Figure 2-3: Upflow Anaerobic Sludge Blanket Block Diagram

There are many advantages to UASBs including simplicity in design and installation, small land requirement, low excess sludge production, and energy generation in the form of biogas [7]. In addition, these systems do not vary based on temperature and do not produce as much excess sludge as other technologies such as activated sludge tanks do [7]. Some disadvantages to USABs include long startup time, high construction costs, and the potential for biogas to dissolve into treated effluent water. As such, posttreatment is required with the application of USABs to remove unwanted biogas and other residual contaminants from the effluent [7]. Options for posttreatment commonly include a moving bed biofilm reactor, downflow hanging sponge, or advanced oxidative processes (AOPs). Nevertheless, UASBs are a reliable and effective treatment alternative to reduce BOD, COD, TSS, and TKN.

2.4.3 Membrane Filtration

Membrane filtration technology is a widely used and viable option for the treatment of BOD, COD, and TSS. Implementation of this technology on brewery wastewater has shown BOD, COD, and TSS removal rates of approximately 99% [8]. In addition, membrane filtration systems have high pollutant rejection rates, great durability, and have high permeate flux [8]. These results and characteristics are what make membrane filtration a popular solution for treating brewery wastewater. Membrane filtration systems have high capital and maintenance costs but remain highly practical as they have a high resistance to chemicals [8].

There are many styles of membrane filtration technologies. Among these, reverse osmosis (RO) and nanofiltration (NF) have been proven to be the most effective for brewery wastewater [8]. Figure 2-4 shows a simple configuration of a reverse osmosis membrane filtration treatment solution.

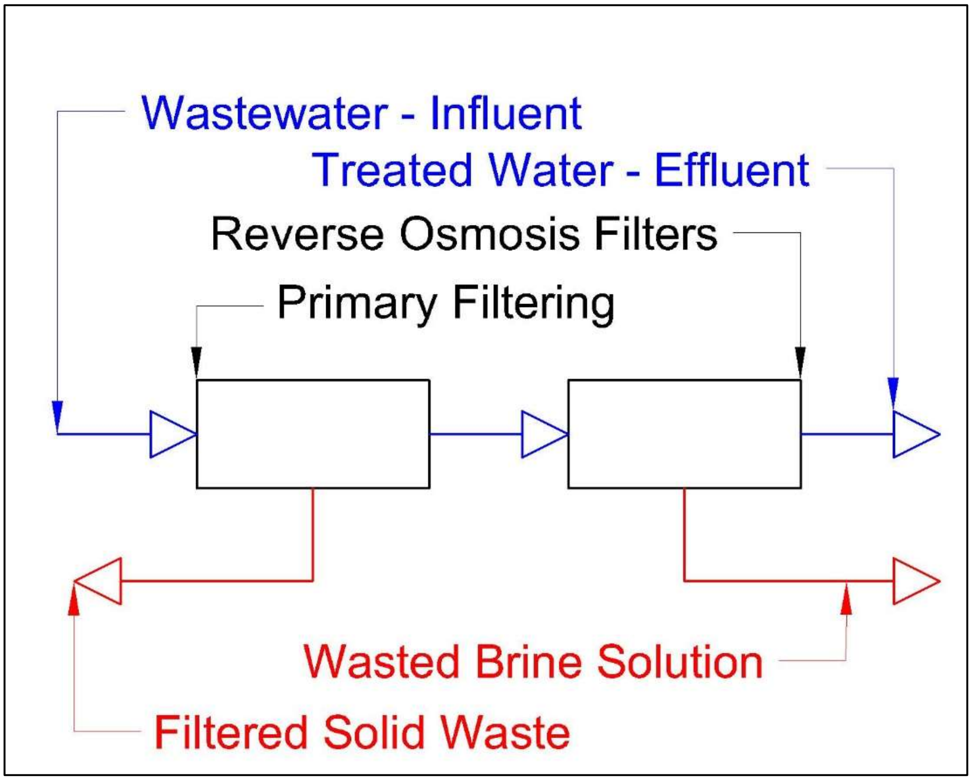

Figure 2-4: Reverse Osmosis Block Diagram

2.4.4 Microalgae Treatment

Microalgae treatment is a biological aerobic treatment alternative that is effective at removing TKN. Specifically, scale trials of microalgae treatment have shown excellent performance in the removal of nitrogen and phosphorus. Results from these trials have shown a 99% removal efficiency of nitrogen and phosphorus in one week of treatment [8].

Microalgae is applicable to wastewater treatment as microalgae digests inorganic nitrogen sources, such as nitrate, nitrite, and ammonium [8]. Given these nutrients and the proper conditions, microalgae can grow exponentially within 3.5 hours [9]. This biological alternative is commonly implemented for wastewater treatment in two methods: raceway ponds and photobioreactors [8]. Raceway ponds are shallow open systems with a semi-circular shape at the ends [8]. A paddle wheels continuously mixes the microalgae in the wastewater, appreciating removal efficiency [8]. An illustration of a raceway pond has been provided in Figure 2-5. Photobioreactors are vertical columns that allow light into the system to fuel photosynthesis [8]. Carbon dioxide is sparged into the column and is circulated to maximize contact between carbon dioxide and algae [8]. An example of a photobioreactor is shown in Figure 2-6.

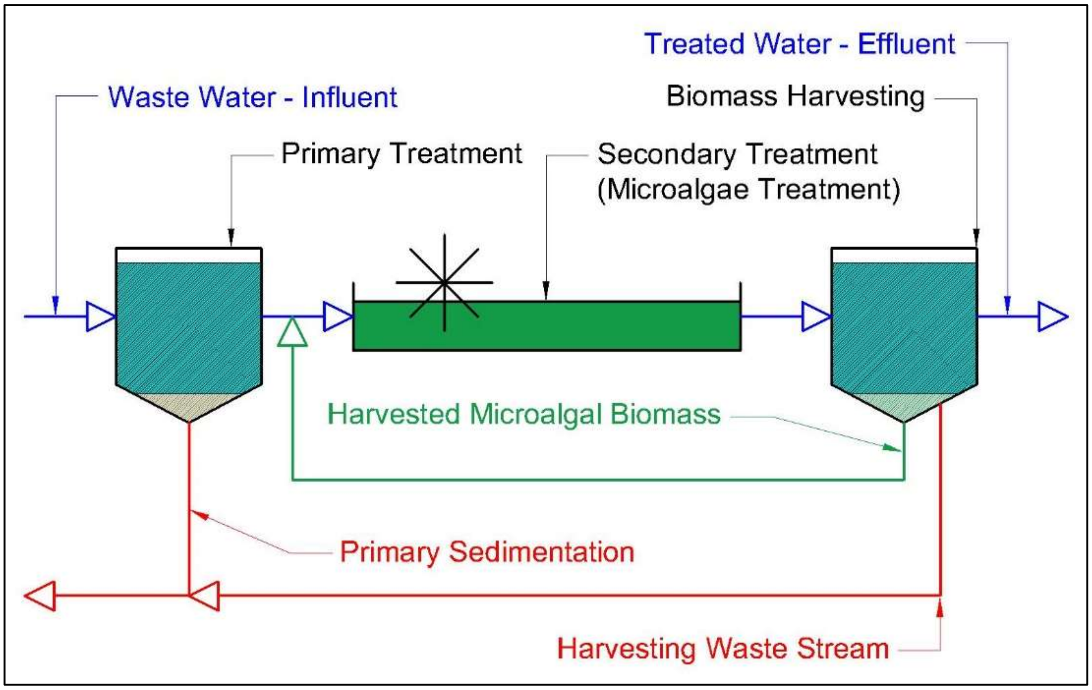

Figure 2-5: Microalgae Treatment - Raceway Pond Block Diagram

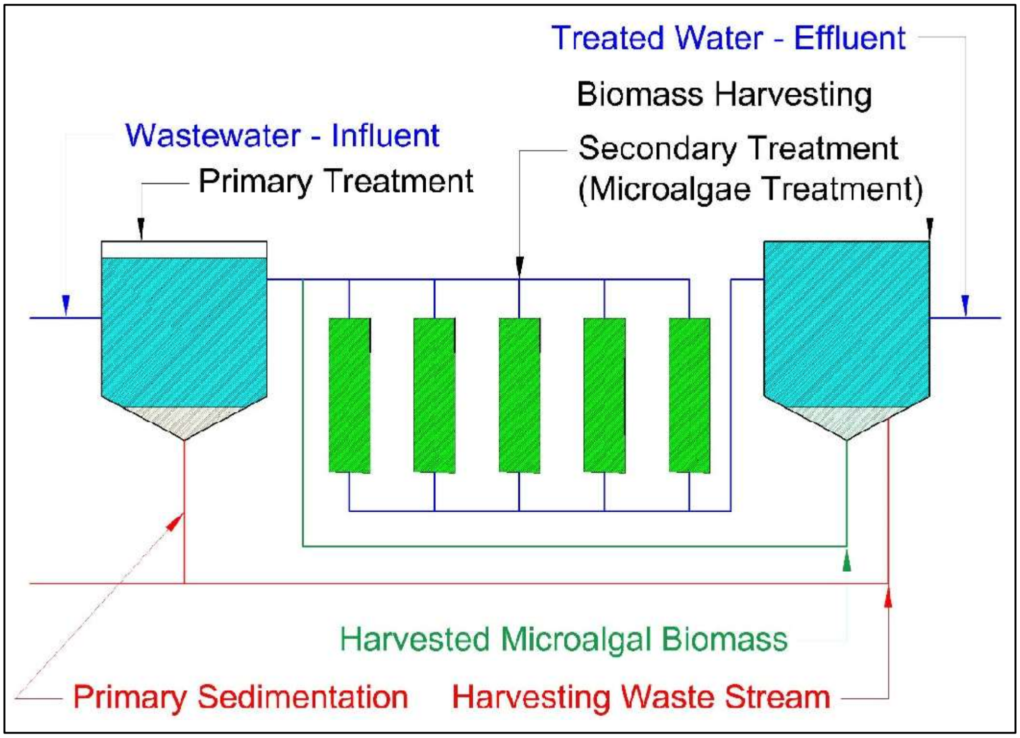

Figure 2-6: Microalgae Treatment - Photobioreactor Block Diagram

The benefits of microalgae include being ubiquitous in nature, rapidly producing, and act as aeration devices that produce oxygen for bacteria [9]. Additionally, microalgae systems produce end products that can be used as animal feed or crop fertilizer [9]. Microalgae systems have lower capital cost, operation costs, and lower energy intensities in comparison to conventional wastewater treatment [9]. With these benefits in mind, there are some disadvantages that have barred wide-scale usage in wastewater treatment processes. Microalgae is highly dependent on lighting, temperature, addition of nutrients, and pH [9]. Among these, pH control poses considerable difficulties as pH levels have been observed to vary within the system. Additionally, microalgae treatment requires an additional step to recover microalgae from raceway effluent called biomass harvesting. Solutions for biomass harvesting include filtration, adding lime and alum, centrifugation, and gravity sedimentation [9]. Although these solutions are successful options, they have also proved to be quite difficult and costly.

2.4.5 Electro-Fenton Sequencing Batch Reactor

Electro-fenton sequential batch reactors (EF-SBR) are a treatment alternative effective at removing TKN and ammonia-based wastewater contaminants. EF-SBRs function as electrochemical-based batch reactor systems. This is accomplished by inserting an anode and a cathode into a wastewater batch reactor. The anode is the negative, reducing electrode which produces hydrogen peroxide and reduces the charge of iron present in the anode [10]. These reactions may be found below:

Equation 2-1: Production of Hydrogen Peroxide [10]

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2$$

Equation 2-2: Reduction of Iron [10]

$$Fe^{3+} + e^- \rightarrow Fe^{2+}$$

The cathode is the positive, oxidizing electrode which oxidizes iron and hydrogen peroxide. These reactions may be found below:

Equation 2-3: Oxidation of Hydrogen Peroxide [10]

$$2H_2O_2 \rightarrow 2O_2 + 4H^+ + 4e^-$$

Equation 2-4: Oxidation of Iron [10]

$$Fe \rightarrow Fe^{2+} + 2e^-$$

Inserting the anode and cathode into an electrolyte (e.g. wastewater) creates an environment which denitrifies water from electrochemical reactions.

In between the anode and cathode, a reaction between the iron and hydrogen peroxide takes place which produces hydroxyl radicals [10]. Such a phenomenon is defined as electro-fenton reactions and proceeds as follows:

Equation 2-5: Production of Hydroxyl Radicals [10]

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + (\cdot OH) + OH^-$$

Where $(\cdot OH)$ denotes a hydroxyl radical. Utilizing hydroxyl radicals as an oxidizer is highly effective in breaking down difficult contaminants such as TKN [10]. Total Kjeldahl nitrogen is a formation of carbon and nitrogen atoms in a cyclic structure. The free hydroxyl radical reacts with the cyclic carbon and nitrogen structure and acts as an oxidizer to break down the TKN [10]. This TKN is converted into biomass. It is also worth noting that not all of the hydrogen peroxide gas in the equation is being used up. There is a leftover amount of hydrogen peroxide that is produced in the process.

Equation 2-6 breaks this process down:

Equation 2-6: Dissociation of TKN

$$(\cdot OH) + TKN + \ H_2O \rightarrow \ C_5H_7O_2N$$

Here, the product has been converted into a sludge mass including carbon, hydrogen, oxygen, and nitrogen. Thus, form of a solid will then settle to the bottom of the reactor as sludge. Nitrogen that precipitated from the dissociation of TKN will then settle to the bottom of the reactor as sludge [10]. Settled sludge may then be removed and disposed. An illustration of the Electro-fenton process is shown in Figure 2-7.

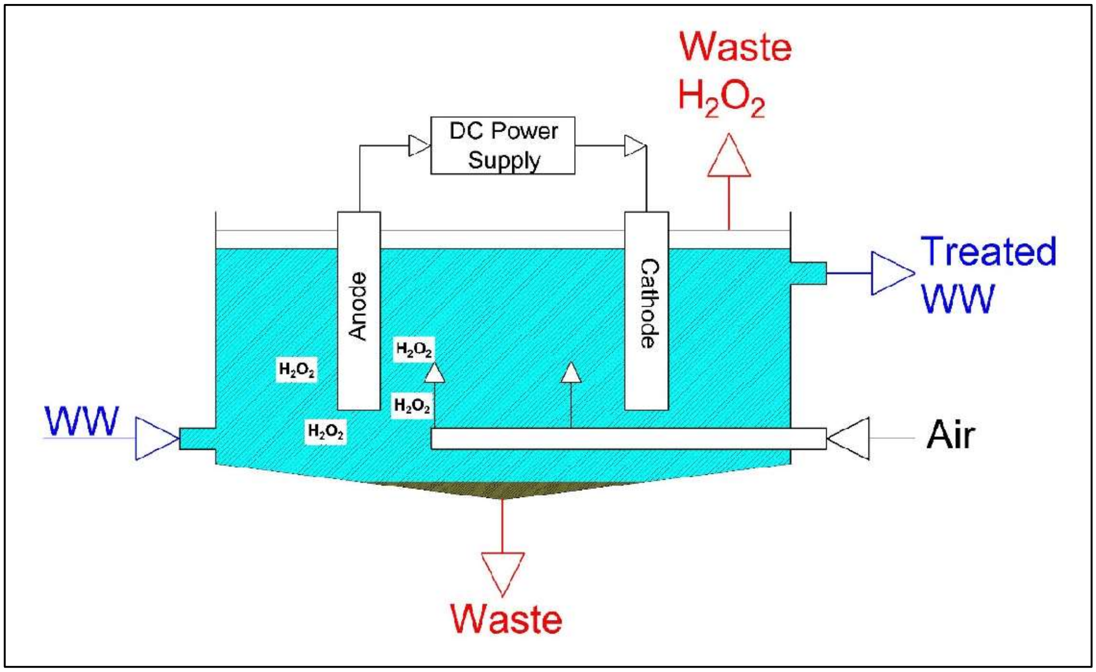

Figure 2-7: Electro-Fenton Sequencing Batch Reactor Block Diagram

Studies of EF-SBRs have shown a 98% removal efficiency of TKN from industrial wastewaters within a 72-hour treatment period [10]. These studies have proven EF-SBRs to effectively treat TKN contamination to acceptable levels [10]. In addition to this alternative's TKN removal efficiency, it also produces low volumes of sludge that must be handled. Benefits of this technology continue with the potential to generate profit because hydrogen peroxide is generated in-situ as a byproduct. Should this byproduct be collected properly at a low cost, it can be sold for financial return [10].

One of the major drawbacks of this technology is that it has not been used in practice at a wastewater treatment plant and is costly to maintain and construct as it uses high-tech equipment. Although the system has not been used in practice, it has great potential considering its extremely high efficiency in research settings. In addition, it is a subcategory of the electrochemical advanced oxidation processes which have been used in practice and have been proven to be reliable and efficient [10].

2.4.6 LEAPmbr™

LEAPmbr™ is a GE Appliances trademark and is a treatment alternative that has shown to be highly efficient for the removal of TKN. This alternative functions as a modified membrane bioreactor. It works using submerged membranes in which are in direct contact with wastewater [11]. A vacuum is applied to a header connected to the membranes and draws the water through the membranes, which filter out solids along with bacteria and viruses [11]. Therefore, the sludge produced by the system is collected on the membrane and disposed of along with the membrane. However, as with all membrane systems, membranes require backwashing and cleaning. Backwashing normally consists of passing water through the system in the direction opposite of normal water flow to remove particulate matter and reduce cleaning to every four to six weeks [12]. Thus, there may be sludge present in the system once the membranes are rinsed that must be collected and disposed of. Once the filter is backwashed, it is regenerated to its original state using diluted rinses of strong acids and bases in caustic soda [12]. Then, the filters are rinsed once again [12]. An illustration of this process has been provided in Figure 2-8 below.

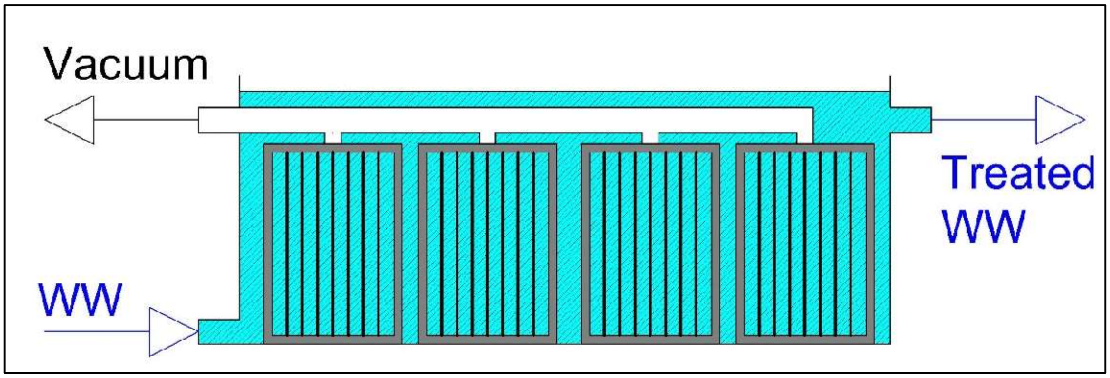

Figure 2-8: LEAPmbr^{TM} Block Diagram

LEAPmbr™ was one of the first technologies made with the intent to address the high cost commonly associated with traditional membrane bioreactors. This has been successfully accomplished as LEAPmbr™ has a lower energy cost, a 50% reduction in membrane aeration equipment, and 30% reduction in physical footprint [11]. These modifications have been implemented while retaining the same organic removal efficiency present in traditional membrane bioreactors. This is supported as the TKN removal efficiency of this alternative is approximately 90% [10].

Despite these improvements, this technology is still expensive regarding membrane maintenance and installation costs and has not been applied as a treatment technology despite its introduction to the field over ten years ago.

2.4.7 Continuously Stirred Tank Reactor (Anaerobic)

A continuously stirred tank reactor (CSTR) operating as an anaerobic digester is a viable option for treating BOD, COD, and TKN [13]. Anaerobic CSTRs operate under steady state conditions as the flow of influent wastewater is always equal to the treated water effluent. Substrate (wastewater) is added to the reactor where a stirrer continuously homogenizes the solution. Continuously mixing the solution allows the biomass to remain in suspension. This maximizes contact between wastewater nutrients and the CSTR's biomass, thus promoting COC removal. Additionally, heat may also be applied to the reactor to further improve treatment efficiency [14].

As this alternative is an anaerobic process, digestion of organics shall result in the production of biogas, primarily methane and carbon dioxide [13]. Gas production within a general anerobic CSTR is estimated to be 70% methane and 30% carbon dioxide. Given proper biogas capture procedures, methane may be recovered and used as an energy source to heat the reactor.

Benefits of anaerobic CSTRs are that they are widely used, suitable for high organic loads, is inexpensive to install, and operates at a steady state. Additionally, this alternative carries the ability for variation, allowing the system to be easily tailored to specific needs. One drawback to this alternative is that it requires a solids removal after treatment if it were to be part of the wastewater treatment plant's process in order to separate biomass and sludge from treated wastewater [14].

Figure 2-9 shows a CSTR with a clarifier used for solids removal.

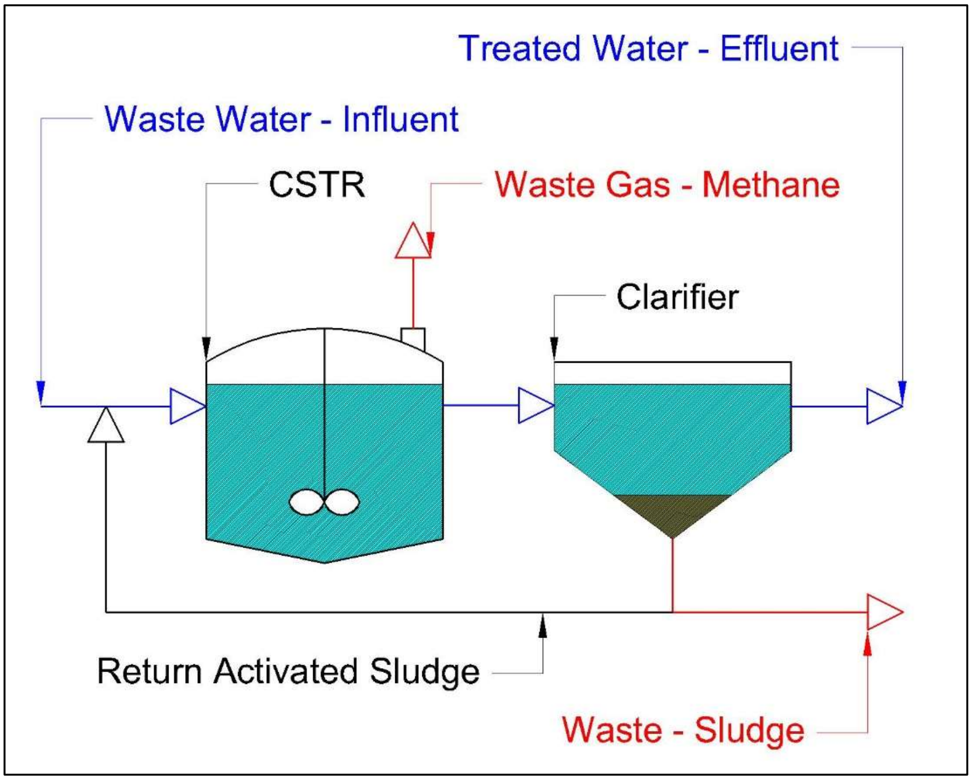

Figure 2-9: Anaerobic CSTR Block Diagram

2.4.8 Hybrid Fixed Bed Membrane Bioreactor

A hybrid fixed bed membrane bioreactor (FBMBR) is a pretreatment alternative that successfully treats BOD, TKN, and TSS in one system.

FBMBR operates as wastewater flows into the bottom of the system's tank. Compressed air is sparged at the bottom of the tank to provide oxygen for the activated sludge and circulate the suspended biomass evenly throughout the unit [15]. The water passes through a membrane to remove larger suspended solids. Then, the water passes into a fixed bed made of rigid material that is used to promote high biofilm surface area [15]. The wastewater flows up through the fixed bed and treated effluent flows out near the top of the unit. A recirculating pump is additionally used to transport a portion of treated water to the beginning of the process to increase biomass suspension [15]. Granulated activated carbon is placed at the bottom of the unit to promote COC removal, increase biofilm growth, and prevent excess activated sludge from accumulating [15]. The system is backwashed weekly to prevent buildup on the membranes and to allow for enhanced performance. The membranes are cleaned every four to six weeks according to the same procedure described in section 2.4.5. An illustration of this system has been provided in Figure 2-10.

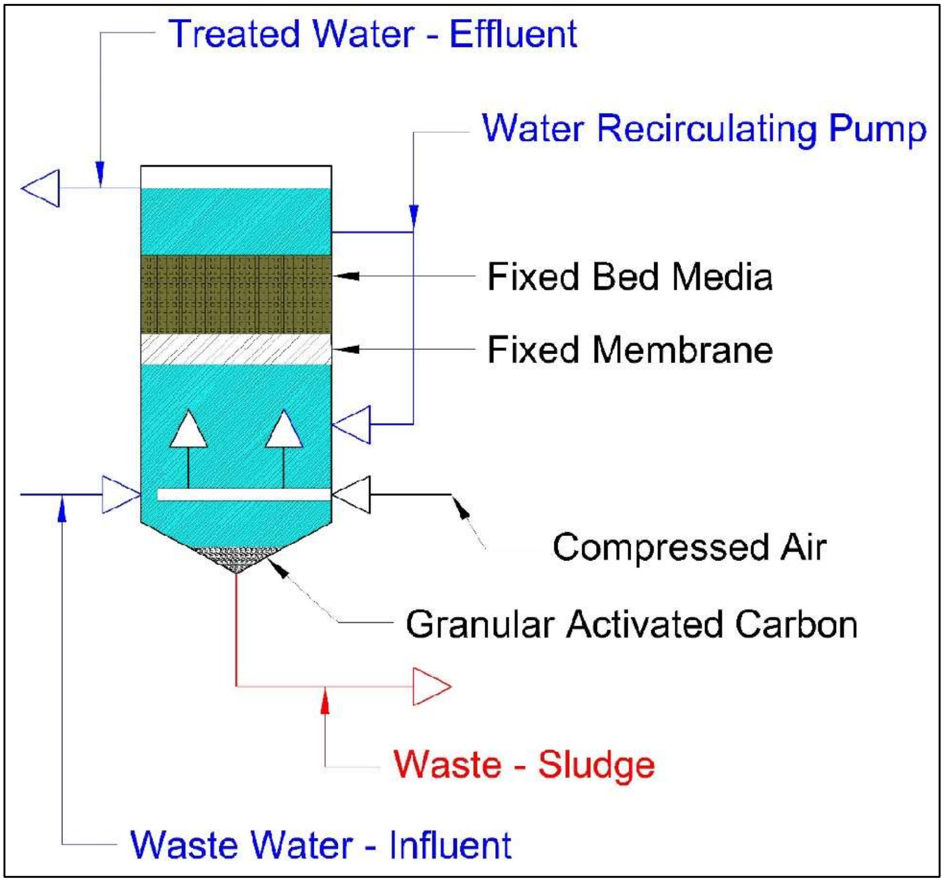

Figure 2-10: Hybrid Fixed Bed Membrane Bioreactor Block Diagram

Under anoxic conditions, FBMBR removes total nitrogen by 49% and BOD, COD, and TSS by 95% [16]. Other benefits include the ability to receive high organic loads, withstand fluctuation in organic loading rates (OLRs), and reduce excess sludge production [16]. However, as with all membrane technologies, FBMBR has a high operational cost associated with replacing membranes before membrane fouling occurs. Additionally, there is not much information on its ability to remove TKN since the nutrient removal efficiency is relatively low even with a total nitrogen removal of 49%.

2.4.9 Settling Tank

Settling tanks are an option for BOD and TSS treatment. Settling tanks are widely used in wastewater treatment processes as they are a reliable, conventional technology.

This alternative operates by introducing water into a settling tank with chemical coagulants (types of chemicals added are dependent upon the contaminants). Gravity acts to pull the suspended solids to the bottom of the tank [17], this phenomenon is additionally promoted by the geometry of the tank's floor. The accumulation of settling solids form a sludge at the bottom of the tank. This sludge is removed as scrapers move along the tank's floor. Floatable solids create a scum at the surface of the water and are removed by a skimming mechanism [17]. Finally, treated water is removed by an effluent weir near the top of the tank. An illustration of this process has been provided below in Figure 2-11.

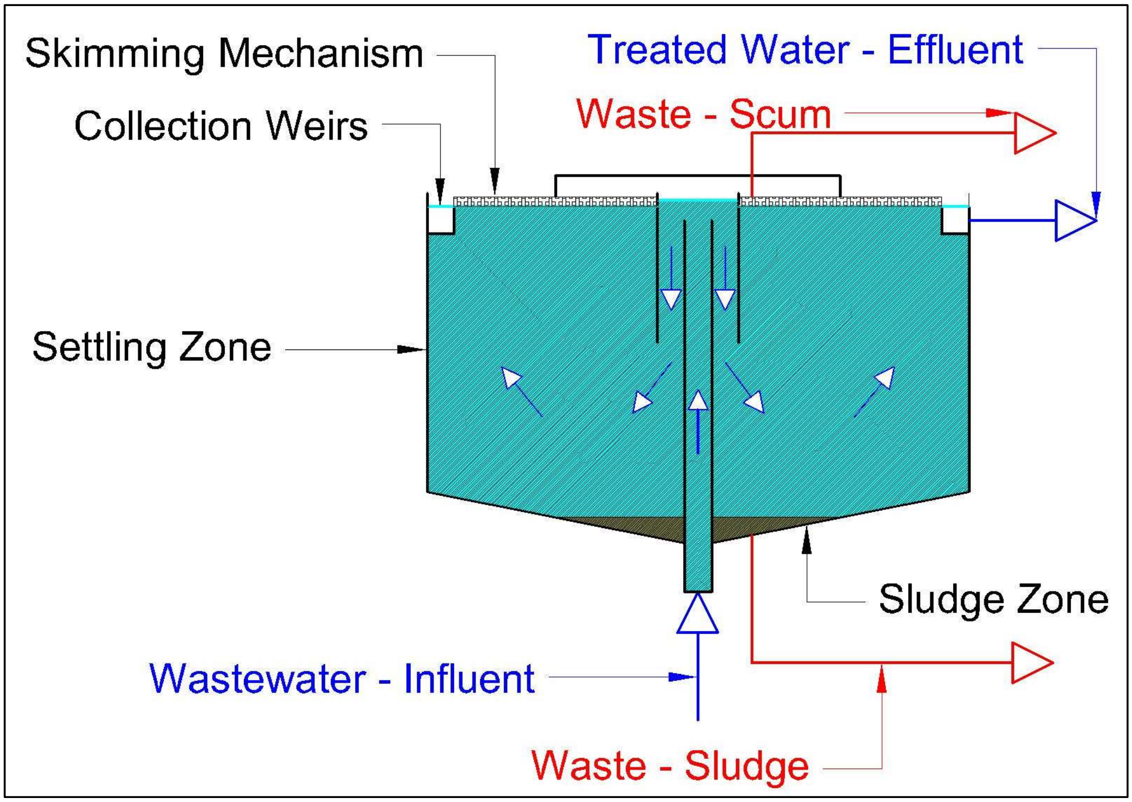

Figure 2-11: Settling Tank Block Diagram

Settling tanks are a physical treatment method and thus removes 50-70% of suspended solids and 25-35% BOD [17]. This system is highly dependent upon the velocity of the water and flocculation of the particles [18]. Therefore, the depth to length ratio of the tank is the most important consideration for the treatment. The system works best in moderate temperatures and is therefore unsuitable for warm climates due to thermal stratification [18] and cold climate due to density current formation which decreases efficiency of sludge collection [18].

2.4.10 Trickling Filter

A trickling filter is a low cost, viable treatment method for BOD, COD, TKN, and phosphorus removal.

Trickling filters operate as wastewater enters through the top of the system and warm, low-density airflow enters the bottom of the unit [19]. Solid media is placed as a fixed bed within the system which acts as a surface to promote biofilm accumulation [19]. The wastewater is then decontaminated through aerobic microbial processes as it trickles down the fixed media and over the biofilm. A clarifier is often required after the trickling filter to settle out any residual biomass from the treated effluent. An illustration of this process has been provided below in Figure 2-12.

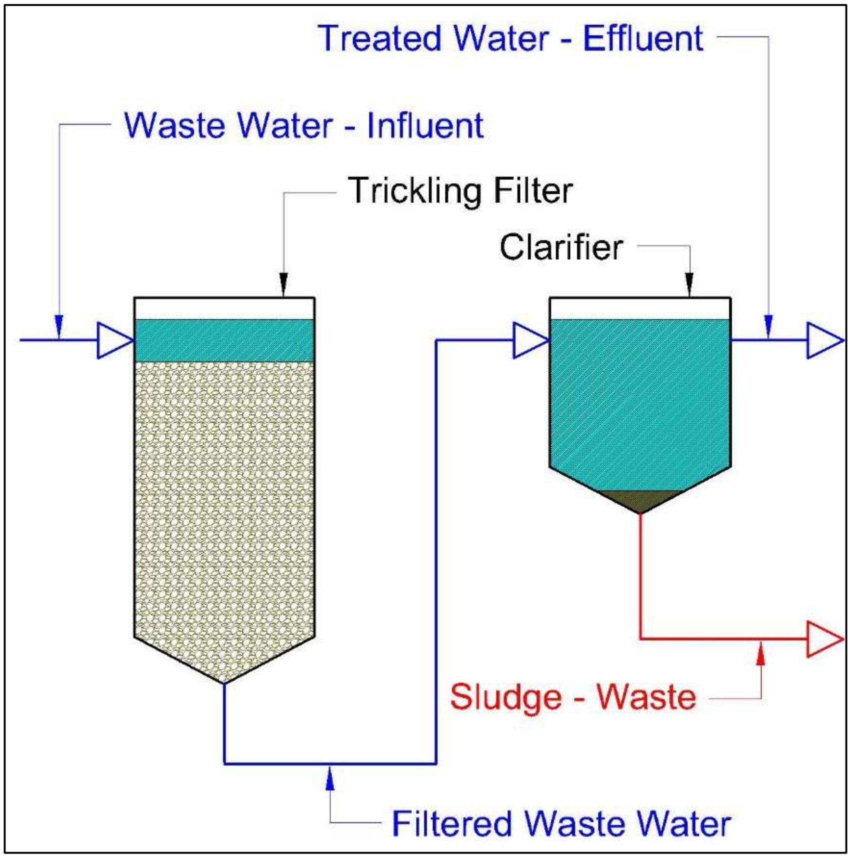

Figure 2-12: Trickling Filter Block Diagram

A study for removal efficiency has been conducted specifically for brewery wastewater and removal efficiencies were found to be 86.53% for COD, 95.25% for BOD, 69.93% for nitrogen, and 41.04% for phosphorus [19]. The filter is also very environmentally sustainable since it uses natural materials and is considered an ideal treatment technology for varying wastewater flows, which is typical of brewery industrial wastewater [19].

2.4.11 Aerobic Sequencing Batch Reactor

An aerobic sequencing batch reactor is a commonly used treatment solution for BOD and COD removal. Aerobic SBRs operate as an activated sludge process in which wastewater is pumped into a batch reactor along with sparged air [20]. Introduced air forms bubbles within the wastewater and activates bacterial populations [20]. Formed bacteria then digests COD and BOD within the influent wastewater. Once the designed hydraulic retention time has been reached in one batch reactor, it is drained directly into a second batch reactor. Within the second reactor the process of anaerobic digestion repeats, further treating the wastewater. Once the hydraulic retention time within the second reactor is completed, treated wastewater is discharged from the process. An illustration of this process has been provided below in Figure 2-13.

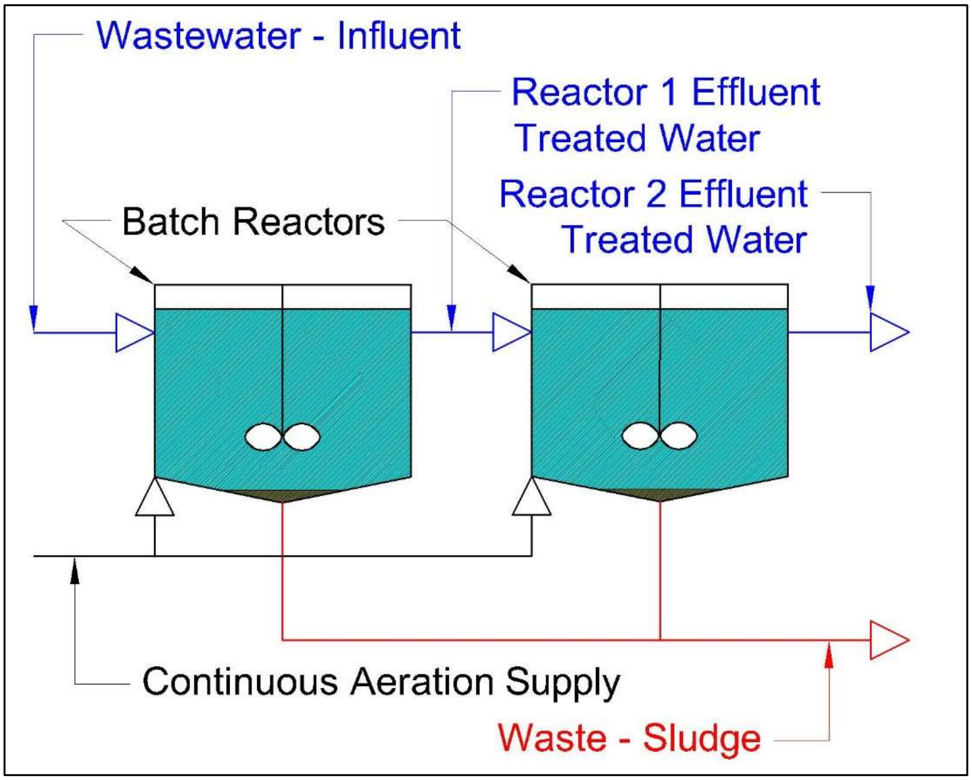

Figure 2-13: Sequencing Batch Reactor Block Diagram

Since brewery wastewater has a high organic content as well as high biodegradability, sequencing batch reactors are a reliable option for treatment [21]. COD removal in a brewery wastewater pilot study was found to be 90% while BOD removal efficiency was found to be 80% [21]. Aerobic SBRs are additionally suitable for high organic loading rates which is a necessary parameter for brewery wastewater [21].

2.5 Preliminary Screening of Technologies

Upon assessing the feasibility for each of the above technologies in relation to the project, microalgae treatment was eliminated from further consideration as it requires sunlight. Since the design will be placed outside of the MRBC facility, the design must be enclosed. Winter months in Flagstaff can be harsh and freezing temperatures will cause the treatment system to not operate properly. Thus, the system must be enclosed to prevent damage to the design and avoid inoperability. Therefore, microalgae treatment is not feasible for this project and is not further considered. Technologies dependent upon temperature were not eliminated at this point since a temperature dependency can be combated by adding a cooling or heating system as needed.

2.6 Test Methods

Weekly COC analysis by Inner Basin Environmental Laboratories (IBE) provided concentration levels of BOD, TKN, and TSS for 8/4/2022 to 2/16/2023 as shown in Figures 1-3, 1-4, and 1-5. Methods used for IBE Lab's analysis include SM 5210 B Biochemical Oxygen Demand (BOD), SM 2540 C Total Dissolved Solids (TSS), and EPA 351.2

Determination of Total Kjeldahl Nitrogen (TKN) as seen in Table 1-1. Although these data were sufficient to begin developing a pretreatment design, testing of these COCs was additionally conducted per the client's suggestion. Additional testing of BOD, TKN, and TSS allows the design to be developed with an increased level of quality control. In addition to the evaluation of these COCs, analysis was also conducted by Still Water Treatment Engineering to evaluate concentrations of volatile suspended solids (VSS), chemical oxygen demand (COD), and phosphates present in MRBC's wastewater to determine the viability of a biological treatment system. Evaluation of these additional COCs yielded pertinent information that informed the selection of the preferred alternative. Specific test methods that were conducted with respect to each COC are shown in Table 2-3 below. Alternative standard methods to IBE Lab's test methods were selected for the analysis of BOD, TSS, and TKN at NAU. This was done because of equipment availability in NAU's environmental engineering laboratory.

Table 2-1: Test Methods

Test Methods		
COC	**Test Method,** NAU	**Test Method,** IBE
BOD	Standard Method 5210	Standard Method 5210
TKN	HACH Method 10242	EPA 351.2
TSS	HACH Method 8158	Standard Method 2540
VSS	HACH Method 8164	N/A
COD	HACH Method 8000	N/A
Phosphates	HACH Method 8048	N/A

3.0 Laboratory Analysis and Results

Laboratory analysis was conducted to confirm COC concentrations provided to MRBC by IBE. COC concentrations are provided by IBE labs on an average biweekly basis and report on BOD, TSS, and TKN levels. Data collected by MRBC has been provided to the team and approximately extends over the last 9 months.

The development of MRBC's pretreatment process was designed to handle the maximum concentrations of COCs. Therefore, values collected from Still Water Treatment Engineering laboratory analysis were compared to values reported by IBE labs, and the greater value between the two was accepted as treatment parameters.

As IBE labs only provide concentration values for BOD, TSS and TKN, the team has additionally evaluated concentrations of VSS, COD, and phosphates (as PO_4). As these values do not have additional data to be compared to, the team accepted values according to the determined accuracy of these results.

The team acquired one-liter samples of wastewater from MRBC's holding tank on February 28, 2023 and March 7, 2023. To prepare the suspended seed for BOD testing, the team acquired mixed liquor suspended solids (MLSS) from the Rio de Flag Wastewater Treatment Plant on

February 28, 2023. All wastewater samples were kept in the refrigerator at NAU's environmental engineering laboratory at 4 ºC until they were used in each testing procedure. This measure ensured quality control as the refrigerator maintained the integrity of the wastewater over time.

3.1 Methodology

Laboratory procedures have been conducted by the team as outlined in Section 2.6: Test Methods. Table 3-1 provides the number of tests conducted for each sample event.

3.1.1 Biological Oxygen Demand

BOD was evaluated according to Standard Method 5210, Biological Oxygen Demand. Utilization of this method entailed the collection and inoculation of a MLSS solution from Rio De Flag wastewater treatment plant, creating suspended seed. Dilution water was prepared with the addition of suspended seed and nutrient solutions created according to the method. Three dilutions and three respective duplicates were prepared in BOD bottles. On March 2, 2023, three samples and one duplicate were evaluated. On March 3, 2023, four samples and three duplicates were prepared. On March 8, 2023, four samples and four duplicates were prepared. Dissolved oxygen readings were recorded at time of preparation and again after five days of incubation.

Equation 3-1 below was used to determine the 5-day biological oxygen demand.

Equation 3-1: 5-Day Biological Oxygen Demand [22]

$$BOD_5, \frac{mg}{L} = \frac{(D_1 - D_2) - (S)V_s}{P}$$

Where:

BOD_5 = 5-day biochemical oxygen demand (mg/L)
D_1 = DO of diluted sample immediately after preparation (mg/L)
D_2 = DO of diluted sample after 5-day incubation (mg/L)
S = Oxygen update of seed (DO/mL)
V_s = Volume of seed in respective test bottle (mL)
P = Decimal volumetric fraction of sample used; 1/P = dilution factor

3.1.2 Total Kjeldahl Nitrogen

TKN was evaluated according to HACH Method 10242, Nitrogen, Simplified TKN. Two vials were prepared in parallel with the sequencing addition of reagents and reaction time. Reagents within this test react within inorganic nitrogen to form nitrate and nitrite. The reading of TKN from this analysis is therefore the sum of nitrate and nitrite. On March 3, 2023, one sample and one duplicate were prepared. On March 9, 2023, an additional sample and one duplicate were prepared. One vial, labeled with a red cap, was used to measure the concentration of nitrate-nitrogen. The other vial, labeled with a green cap, communicated the concentration for nitrite-nitrogen. Added together, the sum of these two values yields the concentration of TKN present in the sample.

Equation 3-2 below was used to determine the TKN concentration present in sample from NO_3-N and NO_2-N readings.

Equation 3-2: Total Kjeldahl Nitrogen [23]

$$\mathrm{NO_3\text{-}N} + \mathrm{NO_2\text{-}N} = TKN$$

Where:

NO_3-N = Nitrate Nitrogen (mg/L)
NO_2-N = Nitrite Nitrogen (mg/L)
TKN = Total Kjeldahl Nitrogen (mg/L)

3.1.3 Total Suspended Solids & Volatile Suspended Solids

TSS and VSS were evaluated sequentially according to HACH Method 8158 and HACH Method 8164 (Solids, Non-Filterable Suspended, Total and Volatile), respectively. A volume of solution was passed through a prepared filter apparatus. The sample collected on the filter was heated at two different temperatures and weighed directly after each heating. The resulting weights allowed for the calculation of total suspended solids and volatile suspended solids. On March 2, 2023 one sample and one duplicate were tested. On March 3, 2023, another sample and duplicate were tested, and on March 9, 2023, one sample and duplicate were tested.

Equation 3-3 below was used to calculate total suspended solids present within the sample.

Equation 3-3: Total Suspended Solids [24]

$$\frac{A - B}{L} = TSS$$

Where:

A = Weight of fiber filter disk with solids (mg)
B = Weight of empty fiber filter disk (mg)
L = Volume of sample (L)
TSS = Total Suspended Solids (mg/L)

Equation 3-4 below was used to calculate volatile suspended solids present within the sample.

Equation 3-4: Volatile Suspended Solids [24]

$$\frac{A - C}{L} = VSS$$

Where:

A = Weight of fiber filter disk with solids (mg)

C = Weight of fiber filter disk after muffle furnace (mg)
L = Volume of sample (L)
VSS = Volatile Suspended Solids (mg/L)

3.1.4 Chemical Oxygen Demand

COD was evaluated according to HACH Method 8000, Oxygen Demand, Chemical. This is a test-in-tube method that includes the sequential addition of reagents and reaction time. COD concentration was evaluated with the use of a spectrophotometer. The first testing procedure occurred on March 2, 2023 with three sample tests with another round of three samples being prepared on March 9, 2023.

3.1.5 Phosphates

Phosphates were evaluated according to HACH Method 8048, Phosphorus, Reactive (Orthophosphate). This method was conducted via sequential addition of reagents and reaction time. Phosphates present in the sample were read by a spectrophotometer and communicated as PO_4^{3-}. Initial testing began on March 3, 2023 with one test and one duplicate. On March 9, 2023, another test with one sample and one duplicate was conducted and completed.

3.2 Laboratory Results and Analysis

Table 3-1 below shows the experimental matrix for number of tests for each sample event.

Table 3-1: Experimental Laboratory Testing Matrix

Parameter	# of Tests Using 1st 1 L Sample	# of Tests Using 2nd 1 L Sample
BOD	11	8
TKN	2	2
TSS	4	2
VSS	4	2
COD	3	3
Phosphates	2	2

Table 3-2 shows the results of the laboratory experiments. Data includes results determined by the team in addition to the 12-month maximum and minimum COC concentrations provided to MRBC by IBE labs. As previously mentioned, the greater value present between tested values and IBE lab's max reported value was accepted for design parameters. Accepted values are highlighted in green.

Table 3-2: BOD, TSS, and TKN Concentrations

COC	Sample Size	Lab Result	Max Reported Value (IBE Data)	Min Reported Value (IBE Data)
BOD (mg/L)	19	1960 ± 811	21075	3108
TKN (mg/L)	4	113 ± 0	211	104
TSS (mg/L)	6	1020 ± 330	1860	120

BOD testing resulted in a value that was considerably lower than the range of expected values given IBE's results that range from 3,108 mg/L to 21,075 mg/L. Comparing these values to tested values raises concern to the accuracy of the team's results. This low concentration of BOD is assumed to be a result of potential error in the conducted procedure. This error is anticipated to reside in the determination of the parameter (*S)* in Equation 3-1. This variable is determined by the proper preparation of a seed control as outlined in Section B.6d of Standard Method 5210 [22]. The team determined the oxygen uptake of the seed but may not have properly added the seed to the sample as the method required. Therefore, error is likely in the determination of the seed parameter, resulting in inaccuracy in the reported BOD concentration. Regardless of the potential errors, the tested BOD value is not greater than the 9-month maximum reported value from IBE labs. Therefore, the IBE maximum concentration was used for modeling calculations.

An error arose in the TKN procedure on March 9, 2023. This error was identified as the addition of a reagent at the incorrect stage of the procedure. Identifying this error resulted in discarding that data point for both the sample and duplicate. Results from the remaining trial fell within the expected range of TKN as it was between the 9-month minimum and maximum as reported by IBE labs. Additionally, the TKN method the team conducted did not consider organic nitrogen which is a critical factor. As such, an increase in discrepancy in comparison to IBE values is predicted. Nevertheless, as the concentration still did not exceed the greatest reported IBE value, the maximum TKN concentration as reported by IBE labs was used for modeling calculations.

The TSS results are discussed below with VSS results.

Table 3-3 shows the results for VSS, COD, and phosphorus (as PO_4^{3-}). As there is no additional data to compare these results to, each tested value has been accepted for design modeling calculations.

Table 3-3: VSS, COD, and Phosphorus Concentrations

COC	Sample Size	Lab Result
VSS (mg/L)	6	937 ± 307
COD (mg/L)	6	14916 ± 5703
PO4 (mg/L)	4	7.04 ± 2

All lab testing raw data corresponding to this analysis has been provided in Appendix B.

Three trials (sample and duplicate included) were conducted for the evaluation of TSS and VSS. The presence of error was identified in the first scheduled trial as the fiber filter quickly became saturated with the addition of sample. Upon removal of the filter apparatus, it was noticed that there was a small leakage of sample solution onto the apparatus. This leakage was noted the procedure was continued. Results from this trial were within the expected range. In total, three conclusive results were averaged to provide the TSS and VSS values reported in Table 3-1 and Table 3-2, respectively. TSS values were highly comparable to MRBC's recorded TSS values as can be seen by Table 3-3, suggesting a high level of accuracy. Tested TSS values do not exceed the max reported value from MRBC, therefore 9-month max reported from MRBC was used for modeling calculations.

Volatile suspended solids are the amount of undissolved organic matter in a sample. The majority of TSS in brewery wastewater is expected to be VSS (about 60% [25]); in these tests, the value was 92%. The tested maximum value was accepted for modeling calculations.

COD and phosphate results were determined to be accurate. Typical orthophosphates levels seen in brewery wastewater range from 7.51 mg/L to 74.10 mg/L [25]. However, these values are industrial brewery wastewater values, and not small-scale brewery waste values where lower concentrations of phosphates are usually reported. Therefore, these values were used for modeling calculations.

3.3 Discussion

In order to remove the organic and inorganic material in the wastewater, an aerobic or anaerobic biological treatment method is suggested for wastewater with high amounts of chemical oxygen demand. Since chemical oxygen demand is defined as the measure of oxygen consumed by a chemical reaction, there is a high availability of oxygen in the sample, making a biological treatment solution suitable for the project purpose. In finding a high concentration of COD in the sample, a biological treatment method's use to treat the wastewater is confirmed.

Phosphates are chemical compounds that contain phosphorus, an important parameter to keep low in water bodies because an excess of phosphorus can lead to eutrophication, the rapid growth of algae and aquatic plants that is harmful for aquatic wildlife. This is seen due to an increased growth of plants and algae that takes available oxygen away from other aquatic species. Since the phosphate concentration is low, treatment for phosphates is not necessary. In addition, a biological treatment solution is suitable due to the low concentration.

Additionally, VSS is ignitable which is an important parameter in determining the selected treatment method. Since the VSS concentration is high, this confirms that a biological treatment solution is suitable for the project.

In conclusion, from the VSS, COD, and phosphates testing, a biological treatment solution is suitable and suggested for the project.

4.0 Selection of Treatment Alternatives

Based upon the information in Section 2.0, a total of ten technologies were considered for further evaluation. These technologies are shown in **Error! Reference source not found.**.

Table 4-1: Pre-Treatment Technologies and Reduction of BOD and TKN

Technology	BOD	TKN
Dissolved Air Flotation	X	
Upflow Anaerobic Sludge Blanket	X	X
Membrane Filtration	X	
Electro-Fenton Sequential Batch Reactor		X
LEAPmbr™		X
Continuously Stirred Tank Reactor	X	X
Hybrid Fixed Bed Membrane Bioreactor	X	X
Settling Tank	X	
Trickling Filter	X	X
Aerobic Sequencing Batch Reactor	X	

A set of initial decision matrices were created to identify the most feasible alternatives. These initial decision matrices used the following criteria: capital/installation cost, respective removal efficiencies, physical footprint, environmental dependency, and reliability. Capital/installation cost has been calculated for each technology in Table 4-2 based on the size constraint of 8’ x 20’. Respective removal efficiencies have been reproduced in Table 4-2 for each COC as identified in Section 2.4. These two criteria are quantitative and have been scored accordingly.

Physical footprint considers the descriptions given in Section 2.4 for each technology given that the technology has been tested and approved to be easily reduced in size or if the technology is generally used for projects larger or smaller than 8’ x 20’. Environmental dependency considers whether the given technology’s operability and efficiency depends on temperature, pH, or certain types of microbes. Finally, reliability considers whether the technology has been used in practice or has not been used. Physical footprint, environmental dependency, and reliability are qualitative data since there are no numerical values associated with each.

Two decision matrices were developed to rate and score technologies based on BOD and TKN removal. Each decision matrix was scored based on qualitative (physical footprint, environmental dependency, reliability) and quantitative data (capital/installation cost, removal efficiency).

Table 4-2 shows each of the above criteria and subsequent description for each technology:

Table 4-2: Technology Description in Reference to Criterion

Technology	Reliability	Capital/Installation Cost	Physical Footprint	Removal Efficiency	System Type	Environmental Dependencies
Dissolved Air Flotation	Has been used in practice	$20,000-$30,000 [26]	Larger than 8' x 20'	BOD: 50%	Biological (Aerobic)	Aerobic microorganisms
Upflow Anaerobic Sludge Blanket	Has been used in practice	$70,000-$80,000 [27]	Easily expanded or contracted	BOD: 80% TKN: 98.3%	Biological (Anaerobic)	Anaerobic (Anammox) microorganisms only, pH
Membrane Filtration	Has been used in practice	$40,000-$60,000 [28]	Easily expanded or contracted	BOD: 99%	Physical	N/A
Electro-Fenton Sequential Batch Reactor	Has not been used in practice	Over $100,000 [10]	Easily expanded or contracted	TKN: 98%	Biological and Chemical	N/A
LEAPmbr™	Has not been used in practice	Over $100,000 [11]	Easily expanded or contracted	TKN: 90%	Chemical and Biological	N/A
Continuously Stirred Tank Reactor	Has been used in practice	$15,000-$25,000 [29]	Easily expanded or contracted	BOD: 80% TKN: 40%	Biological (Anaerobic)	Anaerobic microorganisms
Hybrid Fixed Bed Membrane Bioreactor	Has been used in practice	$40,000-$60,000 [30]	Easily expanded or contracted	BOD: 95% TKN: 49%	Biological (Anoxic)	Anoxic microorganisms
Settling Tank	Has been used in practice	$40,000-$60,000 [31]	Easily expanded or contracted	BOD: 30%	Physical	Dependent upon temperature
Trickling Filter	Has been used in practice	$5,000-$10,000 [32]	Smaller than 8' x 20'	BOD: 95% TKN: 70%	Biological (Aerobic)	Aerobic microorganisms
Aerobic Sequencing Batch Reactor	Has been used in practice	$15,000-$40,000 [33]	Easily expanded or contracted	BOD: 80%	Biological (Aerobic)	Aerobic microorganisms

For the quantitative data, removal efficiency had a higher weighted percentage (60%) than capital/installation cost (40%) because the client has expressed that as long as the technology lowers the COC concentrations, the capital/installation cost is not as important so long as the cost is under budget.

Among the qualitative data, physical footprint had the highest weight (50%) since the designed technology must meet the critical project constraint of 8' x 20'. Reliability is crucial for the project considering the chosen technology would preferably be proven and commonly used in environmental engineering practices. Thus, reliability had the second highest weight (40%). Since the designed system will be placed outside, the selected technology's environmental dependency is important for the system to operate. Therefore, environmental dependency (weighted at 10%) is an important parameter but is not as important as meeting the size constraint or being reliable.

Overall, the quantitative data were weighted at 75% of the overall score and the qualitative data were weighted at 25% of the overall score. This was done because the quantitative data are based upon the client's priorities and are credited with having higher merit.

Error! Reference source not found. Table 4-3 shows each criteria weighting as described above:

Table 4-3: Decision Matrix Criteria Weighting

	Quantitative Data	**Qualitative Data**
Percent of Total Score	**75%**	**25%**
Capital/Installation Cost	40%	N/A
Researched Efficiency	60%	N/A
Physical Footprint	N/A	50%
Environmental Dependency	N/A	10%
Reliability	N/A	40%

The scoring system used was a 1-10 (worst to best) system for the quantitative data. **Error! Reference source not found.** displays the scoring system for the quantitative data:

Table 4-4: Quantitative Data Criteria Scoring System

Score	Capital/Installation Cost	Removal Efficiency Range
1	$90,000+	1-9%
2	$80,001-$90,000	10-19%
3	$70,001-$80,000	20-29%
4	$60,001-$70,000	30-39%
5	$50,001-$60,000	40-49%
6	$40,001-$50,000	50-59%
7	$30,001-$40,000	60-69%
8	$20,001-$30,000	70-79%
9	$10,001-$20,000	80-89%
10	$5,000-$10,000	90%+

Table 4-5 shows the quantitative descriptions for the BOD removal technologies that will be used to score each technology:

Table 4-5: BOD Quantitative Descriptions

Technology	Capital/Installation Cost	BOD Removal Efficiency
Dissolved Air Flotation	$20,000-$30,000 [26]	50%
Upflow Anaerobic Sludge Blanket	$70,000-$80,000 [27]	80%
Membrane Filtration	$40,000-$60,000 [28]	99%
Continuously Stirred Tank Reactor	$15,000-$25,000 [29]	80%
Hybrid Fixed Bed Membrane Bioreactor	$40,000-$60,000 [30]	95%
Settling Tank	$40,000-$60,000 [31]	30%
Trickling Filter	$5,000-$10,000 [32]	95%
Aerobic Sequencing Batch Reactor	$15,000-$40,000 [33]	80%

Table 4-6 displays the quantitative score and subscore (based on 40% for cost and 60% for removal efficiency) for each BOD technology:

Table 4-6: BOD Quantitative Scoring

Technology	**Capital Cost Score**	**Subscore (40%)**	**BOD Removal Efficiency Score**	**Subscore (60%)**
Dissolved Air Flotation	8	3.2	6	3.6
Upflow Anaerobic Sludge Blanket	3	1.2	9	5.4
Membrane Filtration	6	2.4	10	6
Continuously Stirred Tank Reactor	9	3.6	9	5.4
Hybrid Fixed Bed Membrane Bioreactor	6	2.4	10	6
Settling Tank	6	2.4	4	2.4
Trickling Filter	10	4	10	6
Aerobic Sequencing Batch Reactor	8	3.2	9	5.4

Table 4-7 shows the quantitative descriptions for the TKN removal technologies that will be used to score each technology:

Table 4-7: TKN Quantitative Descriptions

Technology	**Capital/Installation Cost**	**TKN Removal Efficiency**
Upflow Anaerobic Sludge Blanket	\$70,000-\$80,000 [27]	98.3%
Electro-Fenton Sequential Batch Reactor	Over \$100,000 [10]	98%
LEAPmbr™	Over \$100,000 [11]	90%
Continuously Stirred Tank Reactor	\$15,000-\$25,000 [29]	40%
Hybrid Fixed Bed Membrane Bioreactor	\$40,000-\$60,000 [30]	49%
Trickling Filter	\$5,000-\$10,000 [32]	70%

Table 4-8 displays the quantitative score and subscore (based on 40% for cost and 60% for removal efficiency) for each TKN technology:

Table 4-8: TKN Quantitative Scoring

Technology	**Capital Cost Score**	**Subscore (40%)**	**TKN Removal Efficiency Score**	**Subscore (60%)**
Upflow Anaerobic Sludge Blanket	3	1.2	10	6
Electro-Fenton Sequential Batch Reactor	1	.4	10	6
LEAPmbr™	1	.4	10	6
Continuously Stirred Tank Reactor	9	3.6	5	3
Hybrid Fixed Bed Membrane Bioreactor	6	2.4	5	3
Trickling Filter	10	4	8	4.8

Scores for qualitative data have been given as 0, 5, or 10 since the qualitative data did not vary as much as the quantitative data. Scoring was as follows: low = 0, median = 5, or high = 10 and is shown in Table 4-9 below.

Table 4-9: Qualitative Data Criteria Scoring System

Scores:	**0**	**5**	**10**
Physical Footprint	Normally greater than 8’ x 20’ in area	Can be easily decreased in area	Normally less than 8’ x 20’ in area
Environmental Dependency	More than one dependency	One dependency	Zero dependency
Reliability	Has not been used in practice	N/A	Has been used in practice

The physical footprint was ranked according to how large the system’s area generally is. Specific to this project, the size of each system must fit the size constraint, 8’ x 20’, as described in Section 1.4. If the technology is known to be easily reduced or increased in size while maintaining the original efficiency, it received a median score of 5. Environmental dependency was scored based on if the technology was dependent upon one environmental factor, being temperature, microorganism type, or pH. If a technology had one dependency, it received a median score while a technology with zero dependency received the highest score, and a technology with more than one environmental dependency received the lowest score.

Table 4-10 displays the qualitative descriptions for each BOD removal technology:

Table 4-10: BOD Qualitative Descriptions

Technology	**Reliability**	**Physical Footprint**	**Environmental Dependencies**
Dissolved Air Flotation	Has been used in practice	Larger than 8’ x 20’	Aerobic microorganisms
Upflow Anaerobic Sludge Blanket	Has been used in practice	Easily expanded or contracted	Anaerobic (Anammox) microorganisms only, pH
Membrane Filtration	Has been used in practice	Easily expanded or contracted	N/A
Continuously Stirred Tank Reactor	Has been used in practice	Easily expanded or contracted	Anaerobic microorganisms
Hybrid Fixed Bed Membrane Bioreactor	Has been used in practice	Easily expanded or contracted	Anoxic microorganisms
Settling Tank	Has been used in practice	Easily expanded or contracted	Dependent upon temperature
Trickling Filter	Has been used in practice	Smaller than 8’ x 20’	Aerobic microorganisms
Aerobic Sequencing Batch Reactor	Has been used in practice	Easily expanded or contracted	Aerobic microorganisms

Table 4-11 displays the qualitative score and subscore (50% for physical footprint, 40% for reliability, and 10% for environmental dependency) for each BOD technology:

Table 4-11: BOD Qualitative Scoring

Technology	**Reliability Score**	**Subscore (40%)**	**Physical Footprint Score**	**Subscore (50%)**	**Environmental Dependency Score**	**Subscore (10%)**
Dissolved Air Flotation	10	4	0	0	5	.5
Upflow Anaerobic Sludge Blanket	10	4	5	2.5	0	0
Membrane Filtration	10	4	5	2.5	10	1
Continuously Stirred Tank Reactor	10	4	5	2.5	5	.5
Hybrid Fixed Bed Membrane Bioreactor	10	4	5	2.5	5	.5
Settling Tank	10	4	5	2.5	5	.5
Trickling Filter	10	4	10	5	5	.5
Aerobic Sequencing Batch Reactor	10	4	5	2.5	5	.5

Table 4-12 displays the qualitative descriptions for each TKN removal technology:

Table 4-12: TKN Qualitative Descriptions

Technology	**Reliability**	**Physical Footprint**	**Environmental Dependencies**
Upflow Anaerobic Sludge Blanket	Has been used in practice	Easily expanded or contracted	Anaerobic (Anammox) microorganisms only, pH
Electro-Fenton Sequential Batch Reactor	Has not been used in practice	Easily expanded or contracted	N/A
LEAPmbr™	Has not been used in practice	Easily expanded or contracted	N/A
Continuously Stirred Tank Reactor	Has been used in practice	Easily expanded or contracted	Anaerobic microorganisms
Hybrid Fixed Bed Membrane Bioreactor	Has been used in practice	Easily expanded or contracted	Anoxic microorganisms
Trickling Filter	Has been used in practice	Smaller than 8' x 20'	Aerobic microorganisms

Table 4-13 displays the qualitative score and subscore (50% for physical footprint, 40% for reliability, and 10% for environmental dependency) for each TKN technology:

Table 4-13: TKN Qualitative Scoring

Technology	**Reliability Score**	**Subscore (40%)**	**Physical Footprint Score**	**Subscore (50%)**	**Environmental Dependency Score**	**Subscore (10%)**
Upflow Anaerobic Sludge Blanket	10	4	5	2.5	0	0
Electro-Fenton Sequential Batch Reactor	0	0	5	2.5	10	1
LEAPmbr™	0	0	5	2.5	10	1
Continuously Stirred Tank Reactor	10	4	5	2.5	5	.5
Hybrid Fixed Bed Membrane Bioreactor	10	4	5	2.5	5	.5
Trickling Filter	10	4	10	5	5	.5

Table 4-14 shows the decision matrix for BOD technologies:

Table 4-14: BOD Decision Matrix

	Quantitative Subtotal	Weighted Score (75%)	Qualitative Subtotal	Weighted Score (25%)	Grand Total
Hybrid Fixed Bed Membrane Bioreactor	8.4	6.30	7	1.75	8.05
Anaerobic CSTR	9	6.75	7	1.75	8.50
Upflow Anaerobic Sludge Blanket	6.6	4.95	6.5	1.63	6.58
Trickling Filter	10	7.50	9.5	2.38	9.88
Dissolved Air Floatation	6.8	5.10	4.5	1.13	6.23
Membrane Filtration	8.4	6.30	7.5	1.88	8.18
Settling Tank	4.8	3.60	7	1.75	5.35
Aerobic Sequencing Batch Reactor	8.6	6.45	7	1.75	8.20

Subscores in Table 4-6 and Table 4-11 were summed to get a quantitative and qualitative subtotal. The subscores were multiplied by their respective weights to achieve a weighted score. The weighted scores were summed to calculate a grand total.

Overall, the anerobic CSTR and trickling filter received the highest grand total scores (highlighted in pink) due to their reliability, low capital cost, and high BOD removal efficiencies, and were included in the modeling analysis.

Error! Reference source not found. shows the decision matrix for TKN technologies:

Table 4-15: TKN Technologies Decision Matrix

	Quantitative Subtotal	Weighted Score (75%)	Qualitative Subtotal	Weighted Score (25%)	Grand Total
Hybrid Fixed Bed Membrane Bio-Reactor	5.4	4.05	7	1.75	5.80
Anaerobic CSTR	6.6	4.95	7	1.75	6.70
Upflow Anaerobic Sludge Blanket	7.2	5.40	6.5	1.63	7.03
Trickling Filter	8.8	6.60	9.5	2.38	8.98
Electro-Fenton Sequential Batch Reactor	6.4	4.80	3.5	0.88	5.68
LEAPmbr	6.4	4.80	3.5	0.88	5.68

Subscores in Table 4-8 and Table 4-13 were summed to get a quantitative and qualitative subtotal. The subscores were multiplied by their respective weights to achieve a weighted score. The weighted scores were summed to calculate a grand total.

Overall, the trickling filter and UASB scored the highest for the grand total score and are highlighted in pink.

As a result of the two decision matrices, the top two technologies from each matrix were chosen to be modeled. Since the trickling filter scored the highest for both matrices, three technologies in total were modeled instead of four. Modeled results for each selected alternative, including the trickling filter, UASB, and anaerobic CSTR are found in the following section. The selected alternatives have been modeled rather than fully designed since the alternatives are in their preliminary stages before a preferred alternative is selected.

5.0 Modeling of Alternatives

5.1 Biological Reaction Equations

Equations in the following subsection communicates selected half-reactions. Appropriate half-reactions have been selected according to the electron donor (R_d), electron acceptor (R_a), and cell-synthesis (R_c) that correspond to brewery wastewater. The produced general reaction (R) describes chemical interactions and biodegradation within a reactor.

The general reaction, R, is developed from Equation 5-1 below. Equation 5-1 generates a reaction from the chosen electron donor, electron acceptor, and cell-synthesis half reactions. The interactions described in this general reaction are the rates that products form during microbial digestion. Additionally, this general reaction aids in the determination of the Growth Yield Factor (Y). The Growth Yield Factor is a coefficient that quantitatively describes the mass of biomass produced per mass substrate. This coefficient shall be further discussed in Section 5.3. Two adjustment factors, f_e and f_s, are the percentage adjustment for energy generation and synthesis reaction, respectively. These adjustment factors are specific to aerobic and anaerobic reactions. For aerobic reactions, f_e and f_s have the values 0.1 and 0.9, respectively. For anaerobic reactions, f_e and f_s have the values 0.9 and 0.1, respectively.

Equation 5-1: Half Reaction Combination Equation (R) [34]

$$R = f_e R_a + f_s R_c - R_d$$

Where:

R = General stoichiometric reaction (unitless)
f_e = The percentage adjustment factor for the energy generation (unitless)
f_s = The percentage adjustment factor for the synthesis reaction (unitless)
R_d = Electron Donor Half Reaction (unitless)
R_a = Electron Acceptor Half Reaction (unitless)
R_c = Cell Synthesis Half Reaction (unitless)

In utilizing the appropriate half-reactions in Equation 5-1 and relevant adjustment factors the general reactions, R, for aerobic and anaerobic systems were produced. These general equations describe how microbes within the treatment system interact with the wastewater on a chemical level. The key benefit to this is the ability to predict how much biomass (sludge) shall be produced per unit volume of influent substrate. Additional benefits include perspective into byproducts (e.g. methane and carbon dioxide) that are produced from biological treatment. Determining these values are crucial preliminary steps to design a digital model as they yield insight to reactor behavior.

5.1.1 Electron Donor

An electron donor half reaction describes a reduction reaction in which an incoming compound is broken down to release an electron. There are several complete reduction reactions that may be selected according to the reduced compound (e.g., benzene, ethanol, and methane). Although, for the case of MRBC's wastewater, the electron donor comes from an organic material within the brewery's effluent. As such, the reaction for a custom organic half-reaction has been selected.

Equation 5-2 shows the reaction for a custom organic half reaction. Within this equation, the organic material (substrate) is represented by the compound $C_nH_aO_bN_c$. Here, organic material reacts with water and releases an electron upon reduction. Within this reduction reaction, hydrogen, bicarbonate, ammonia, and carbon dioxide are released. The stoichiometry of this equation is determined by the value of carbon, hydrogen, oxygen, and nitrogen present within the organic compound $C_nH_aO_bN_c$ on the right side. Although this equation implies the formation of the organic compound, it is important to note that this reaction must be utilized with additional half reactions (it cannot be used alone). When utilized to produce a general reaction, organic material will be broken down. This shall be detailed in Section 5.2.

Equation 5-2: Electron Donor for Organics Half-Reaction (R_d) [34]

$$R_d = \frac{(n-c)}{d}CO_2 + \frac{c}{d}NH_4^+ + \frac{c}{d}HCO_3^- + H^+ + e^- = \frac{1}{d}C_nH_aO_bN_c + \frac{2n-b+c}{d}H_2O$$

Where:

$C_nH_aO_bN_c = C_{13}H_{23}O_9N$
$d = 4n + a - 2b - 3c$

The organic material within this equation has been defined as $C_{13}H_{23}O_9N$ as this is the formula that most accurately corresponds to organic biomass found in brewery wastewater.

5.1.2 Electron Acceptor

An electron acceptor half-reaction describes a reaction in which an available compound (e.g. oxygen, nitrate, or carbon dioxide) is consumed. The consumption of this available compound reacts with the electron provided from the electron doner reaction to form its respective products. This phenomenon defines this reaction as an electron acceptor half-reaction.

In the situation of microbiological digestion of wastewater, two separate electron acceptor half-reactions (R_a) may be chosen. If an aerobic pretreatment system is designed, oxygen will be the electron acceptor. Equation 5-3 communicates the existing half-reaction assuming O_2 is the electron acceptor. Equation 5-3 is given the subscript “1” to distinguish this half-reaction from additional electron acceptor half-reactions.

Equation 5-3: Electron Acceptor for O_2 Half-Reaction (R_{a1}) [34]

$$R_{a1} = \frac{1}{4}O_2 + H^+ + e^- = \frac{1}{2}H_2O$$

Utilizing O_2 as the electron acceptor within Equation 5-1 develops a general reaction that describes what happens in aerobic digestion. By developing this equation, the volume of sludge produced, and byproducts can be determined. As this equation is critical to understanding what happens in aerobic digestion, it is additionally pertinent to understanding anaerobic systems. That is, the general reaction resulting from utilizing this half reaction allows the conversion from BOD to biomass. This then allows for the determination of the production of methane when biomass concentrations are input into an anaerobic general reaction.

If an anaerobic pretreatment system is selected, CO_2 will be the electron acceptor. Equation 5-4 describes the half reaction assuming CO_2 as the electron acceptor. Equation 5-4 is given the subscript "2" to distinguish this half-reaction from previous electron acceptor half-reactions.

Equation 5-4: Electron Acceptor for CO_2 Half-Reaction (R_{a2}) [34]

$$\mathrm{R_{a2}} = \frac{1}{8}\mathrm{CO_2} + \mathrm{H^+} + \mathrm{e^-} = \frac{1}{8}\mathrm{CH_4} + \frac{1}{4}\mathrm{H_2O}$$

Utilizing CO_2 as the electron acceptor within Equation 5-1 develops a general reaction that describes what happens in anaerobic digestion. Specific procedures may be required prior to utilizing the general equation resulting from this electron acceptor half-reaction. That is, a general reaction must be developed using Equation 5-1 with O_2 as the electron acceptor. Developing an initial aerobic general equation shall allow the accurate conversion from wastewater BOD concentration to constituents present in an anaerobic general reaction; thus, allowing the determination of produced sludge and byproducts. However, if anaerobic reactants are present within given values, this will not be necessary.

5.1.3 Cell Synthesis

The remaining constituent in Equation 5-1, R_c, is defined as the cell synthesis half-reaction. Cell synthesis half-reactions are chosen according to the appropriate nitrogen source available (e.g., nitrate, nitrite, ammonium). For the case of MRBC's wastewater, ammonium has been selected as the nitrogen source. This is due to the knowledge that ammonium is a primary byproduct of fermentation, as represented by the high TKN concentration in the wastewater. Ammonium's corresponding cell synthesis half reaction is shown below as Equation 5-5. This equation describes the biomass created by the process, as represented by $C_5H_7O_2N$.

Equation 5-5: Cell Synthesis Ammonium as Source Half Reaction (R_c) [34]

$$\mathrm{R_c} = \frac{1}{5}\mathrm{CO_2} + \frac{1}{20}\mathrm{HCO_3^-} + \frac{1}{20}\mathrm{NH_4^+} + \mathrm{H^+} + \mathrm{e^-} = \frac{1}{20}\mathrm{C_5H_7O_2N} + \frac{9}{20}\mathrm{H_2O}$$

The general reactions resulting from these half reactions are described in the following section.

5.2 Results of Biological Reaction Equations

5.2.1 Aerobic General Reaction

Despite the conclusion of modeling an anaerobic system, an aerobic general reaction has been developed. Developing this reaction was necissary as it allowed the estimation of sludge produced according to given BOD concentrations. Estimating sludge production was then used as an input in the anaerobic general reaction to estimate methane and carbon dioxide production. The aerobic general reaction is described as Equation 5-6 below and was determined using Equations 5-2, 5-3, and 5-5 within Equation 5-1.

Equation 5-6: Aerobic General Reaction

$$\frac{21}{793}\mathrm{NH_4^+} + \frac{21}{793}\mathrm{HCO_3^-} + \frac{1}{40}\mathrm{O_2} + \frac{1}{54}\mathrm{C_{13}H_{23}O_9N} = \frac{9}{200}\mathrm{C_5H_7O_2N} + \frac{73}{600}\mathrm{H_2O} + \frac{19}{450}\mathrm{CO_2}$$

This aerobic general reaction was developed in anticipation of determining the methane produced from an anaerobic process. This has been accomplished by determining the amount of $C_{13}H_{23}O_9N$ (substrate) according to the among of oxygen taken up from influent BOD concentrations. The value of substrate present is then used in the following anaerobic general reaction to determine the volume of methane produced by the anaerobic system.

5.2.2 Anaerobic General Reaction

The anaerobic general reaction has been developed to identify the interactions within an anaerobic system. Equation 5-7 below communicates the general reaction developed by utilizing Equations 5-2, 5-4, and 5-5 within Equation 5-1.

Equation 5-7: Anaerobic General Reaction

$$\frac{1}{54}\mathrm{C_{13}H_{23}O_9N} + \frac{19}{300}\mathrm{H_2O} = \frac{1}{74}\mathrm{NH_4^+} + \frac{1}{74}\mathrm{HCO_3^-} + \frac{9}{80}\mathrm{CH_4} + \frac{1}{200}\mathrm{C_5H_7O_2N} + \frac{55}{613}\mathrm{CO^2}$$

This equation has been utilized in parallel with Equation 5-6 to determine the rate at which methane is produced. The method followed to determine this value has been outlined in Section 5.1.2. Utilizing this method has produced a methane (CH_4) production of 2,043 (m^3 CH_4 /day). It is important to note that this volume of methane production is quite large. As such, methane handling options are discussed in Section 6.8. Equation 5-7 has additionally been utilized to determine the Growth Yield Factor (Y). Methodology used to determine Y has will be outlined in Section 5.3.1.

5.3 Modeling Equations

The following set of equations were used to determine various design parameters to determine the size of the treatment units. These equations are dependent upon COC concentrations as well as the biological composition of the wastewater which was identified as described above. These formulas are relevant to almost any biological treatment method and were used to assess how well the selected alternatives perform comparatively.

BOD removal efficiency has been determined using Equation 5-8.

Equation 5-8: BOD Removal Efficiency

$$BOD\ Removal\ Efficiency = \frac{BOD\ Influent - BOD\ Effluent}{BOD\ Influent}\ x\ 100\%$$

Where:

$BOD\ Removal\ Efficiency$ = BOD Removal Efficiency (%)
$BOD\ Effluent$ = Effluent TKN Concentration (mg/L)
$BOD\ Influent$ = Influent TKN Concentration (mg/L)

TKN removal efficiency has been determined to be the base 40% TKN efficiency for anaerobic CSTRs [Table 4-2]. Therefore, the TKN effluent concentration has been calculated according to Equation 5-9 below.

Equation 5-9: TKN Effluent Concentration

$$TKN\ Effluent = 0.4 * TKN\ Influent$$

Where:

$TKN\ Effluent$ = Effluent TKN Concentration (mg/L)
$TKN\ Influent$ = Influent TKN Concentration (mg/L)

5.3.1 Completely Stirred Tank Reactor and Upflow Sludge Blanket Equations

The CSTR and the upflow anaerobic sludge blanket are modeled similarly because they are both anaerobic systems, so the biological requirements are similar. For this reason, the equations for each technology are discussed together.

The growth yield factor (Y) is the ratio between the microbes introduced to the system (C_5 compound, represented as VSS) versus what is produced (C_{12} compound, represented as BOD). This value is outlined below in Equation 5-10.

Equation 5-10: Growth Yield Factor (Y) [36]

$$Y = \frac{g\ C_5H_7O_2N}{g\ C_{12}H_{23}O_9N}$$

The mass of each constituent within this equation has been determined from utilizing the developed anaerobic general reaction (Equation 5-7). Specifically, the growth yield factor is the ratio of grams of biomass to grams of substrate within the equation. Utilizing Equation 5-10 given the anaerobic general reaction (Equation 5-7) produces a growth yield factor of 0.091 g VSS/g BOD.

The half-saturation constant (K) represents the substrate concentration when the rate of substrate utilization is half of its maximum. The substrate in this scenario is the biological population present within influent wastewater, measured as BOD. The half-saturation constant is estimated to be approximately 10 mg BOD/L [35]. This is because the influent wastewater has extremely high concentrations of BOD in addition to little interference from metals and other contaminants hazardous to microbes.

The maximum specific rate of substrate utilization (q) describes how quickly the microbes in the system consume the volatile components of the system. This value was estimated using Table C-1 in Appendix C [36]. This system models an anaerobic system; therefore, the organism type has been identified as methanogens. As such, the maximum specific rate of substrate utilization (q) has been set to the value of 8.4 g BOD/g VSS-d.

The Monod decay constant (b) describes how fast microbes die in a system and is often determined by empirical data. This unitless value was estimated using Table C-1 in Appendix C [36]. Consistent identification of methanogens as the organism type leads to a Monod decay constant value of 0.02.

Equation 5-10 describes the hydraulic retention time given the concentration of microorganisms present in aeration tank. Hydraulic retention time describes how long a particle of fluid will be held within the system.

Equation 5-11: Hydraulic Retention Time [36]

$$\theta = \frac{\theta_x Y(S^0 - S)}{X(1 + b\theta_x)}$$

Where:

θ = Hydraulic Retention Time (days)
θ_x = Solids Residence Time (days)
Y = Growth Yield Factor (gVSS/gBOD)
X = Microorganism Concentration in Aeration (g/L)
S^0 = Influent BOD Concentration (g/L)
S = Required Effluent BOD Concentration (g/L)

Equation 5-11 describes the volume of the tank with respect to hydraulic retention time and flow rate into the tank.

Equation 5-12: Tank Volume [36]

$$\forall = Q\theta$$

Where:

$\forall$ = Volume of Tank (ft^3)
Q = Flowrate into Tank (ft^3/d)

Equation 5-12 describes how to calculate solids retention time (SRT) which is the amount of time solid particles will be retained within the system. This normally limits the hydraulic retention time.

Equation 5-13: Solids Residence Time [36]

$$\frac{1}{\theta_x} = \frac{YqS}{K + S} - b$$

Where:

K = Half Saturation Constant (g/L)
b = Monod Decay Constant (days^{-1})
q = Maximum Specific Rate of Substrate Utilization (gBOD/[gVSS*d])

Equation 5-13 describes the safety factor with respect to the mean cell residence time and the minimum allowable mean cell residence time. The safety factor is used to prevent failure of the system should something fail to perform as expected. Typical safety factors of a system can range from 3-80 based on the biological input and the amount of maintenance/attention that is required to ensure it works properly [37].

Equation 5-14: Safety Factor [36]

$$SF = \frac{\theta_x}{\theta_x^{min}}$$

Where:

SF = Safety Factor of Basin (unitless)
θ_x^{min} = Minimum Allowable Solids Residence (days)

Equation 5-14 describes the organism washout SRT. This value describes the solids retention time at which the system will begin to lose biomass. This value must be met to prevent the microbes of the system from washing out which would cause the existing microbes within the system to be pushed out.

Equation 5-15: Organism Washout Solids Retention Time [36]

$$\theta_x^{min} = \frac{K + S^0}{S^0(Yq - b) - bK}$$

Equation 5-15 is used to determine the minimum substrate concentration that can enter the system.

Equation 5-16: Minimum Substrate Concentration [36]

$$S_{min} = \frac{Kb}{Yq - b}$$

Where:

S_{min} = Minimum Substrate Concentration

5.3.2 Trickling Filter Equations

The following set of equations are used to determine the required flow area and volumes for a trickling filter.

Equation 5-16 is used to determine the hydraulic loading rate of a trickling filter. This value represents the amount of water entering the system based on the surface area.

Equation 5-17: Hydraulic Loading Rate [35]

$$HL = \frac{Q + Q^r}{A_{pv}}$$

Where:
HL = Hydraulic Loading Rate (ft/d)
Q^r = Return Flow Rate (ft^3/d)
A_{pv} = Cross-Sectional Area of Filter (ft^2)

Equation 5-17 represents the BOD Surface Loading Rate. This describes the amount of BOD per area that the BOD interacts with.

Equation 5-18: BOD Surface Loading Rate [35]

$$SL = \frac{QS^0}{A_{pv}da}$$

Where:
SL = Surface Loading Rate (mg/ft^2*d)
d = Depth of Filter (ft)
a = Approximate Area of Filter Media (ft^{-1})

Equation 5-18 describes volumetric loading rate which determines the amount of BOD entering the tank volume per unit volume.

Equation 5-19: Volumetric Loading Rate [35]

$$VL = \frac{QS^0}{A_{pv}d}$$

Where:
VL = Volumetric Loading Rate (mg/ft^3*d)

5.4 Modeling Discussion

The above models do not address the treated levels of TKN because the current concentration range suggests that TKN only needs to be reduced by 18% to meet the standard for discharge; all of the technologies meet this requirement as per Table 4-2. This is because the difference between the measured concentration and the standard is extremely low. For this reason, TKN is not modeled and it is assumed that the treatment systems will remove TKN at the researched efficiencies.

These models are preliminary estimations and are meant to determine the feasibility of these designs. Many of the variables are fixed based upon assumptions and the model does not run multiple scenarios at once.

The models have been run in Excel by varying the adjustable constants in order to get acceptable results as listed in Section 5.5. A sample spreadsheet is provided in Appendix D.

5.5 Results of Modeling

The following section analyzes the results of each model. These models were generated using the equations above and Microsoft Excel. Accompanying Excel work has been provided in Appendix D Anaerobic System Excel Calculations and Appendix E Trickling Filter Excel Calculations.

5.5.1 Completely Stirred Tank Reactor

The following table indicates the optimized design parameters for the CSTR.

Table 5-1: CSTR Design Parameters

Parameter	Value
Hydraulic Retention Time (θ) (days)	0.28
Volume ($\forall$) (ft^3)	299
Solids Retention Time (θ_x) (days)	2.15
Minimum Allowable Cell Residence Time ($\theta_{x\text{-}min}$) (days)	2.15
Safety Factor (SF)	1.00
S_{min} (mg/L)	0.02

The results of the model produce a reasonable volume that meets the prescribed size. The solids retention time is the controlling factor since it determines how long the contaminants in the system are in contact with microbes. This is why SRT was used instead of HRT to calculate both the safety factor and the recirculation rate. The determined safety factor is lower than the required safety factor of 5. This was due to the high BOD loading rate. The low safety factor means that the system is extremely sensitive to operational errors or changes in flow resulting in a system that could potentially fail. The safety factor can be increased by recirculating the solids through the system (increasing the SRT). Further modeling of this option is discussed in Section 7.0. Because of the high BOD concentration and loading rate going into the system, the minimum substrate concentration (S_{min}) is not a concern for this design.

5.5.2 Upflow Anaerobic Sludge Blanket

The modeling data for the UASB is the same as the CSTR due to the biological similarities, but an extra skimming system is required for design. The exact loading rate of the separator cannot be determined without specific sizing of the design and thus was left to the design phase should it be selected as the preferred alternative.

5.5.3 Trickling Filter

The following tables describe the parameters used to design the trickling filter.

Table 5-2 describes the parameters used to generate the trickling filter data. These values are based on the size restriction and information gained from the text: Environmental Biotechnology: Principles and Applications [35].

Table 5-2: Trickling Filter Selected Values

Parameter	Units	Value
Influent Flow Rate (Q)	(ft^3/d)	1086
Return Flow Rate (Q_r)	(ft^3/d)	1000
Cross Sectional Area (A_{pv})	(ft^2)	96
Length (L)	(ft)	16
Width (W)	(ft)	6
Depth (D)	(ft)	7
Media Specific Surface Area (a)	(ft^{-1})	61.0
Influent BOD Concentration (S^0)	(mg/L)	2.1E+04

Table 5-3 describes the results of using the values in Table 5-2 and Equation 5-12 through Equation 5-14 to calculate the loading rates.

Table 5-2: Results of Modeling

Parameter	Value	Typical Values [35]
HL (ft/d)	21.7	131.2
SL mg/(ft^2*d)	1.58E+04	654.2
VL mg/(ft^3*d)	9.62E+05	11.33

The hydraulic loading is a reasonable value for a high-rate trickling filter as suggested by Rittman [35]. However, the calculated surface loading (SL) and volumetric loading (VL) rates greatly exceed the standards for a high-rate filter. This means that the base design is implausible based on the standards obtained from the literature [35]. A low-rate trickling filter was not considered because it is less economical than a high-rate trickling filter, since a high-rate filter removes contaminants at a much faster rate. The contact rate of wastewater per unit cell media is much larger for a high-rate trickling filter because of the combination of a large flowrate and an increase in porous media for this filter.

Table 5-4 represents the required areas and volumes for a high-rate filter based on the design standards for loading rates. This was done to check if the high-rate system could be further designed using recirculation. These values are generated using the information in Table 5-2.

Table 5-1: Required Volumes and Areas Based on Loading Standards [35]

Property	Standard	Volume (ft^3)	Area (ft^2)
HL (ft/d)	131.2	58.0	8.3
SL mg/(ft^2*d)	654.2	16198.4	2314.1
VL mg/(ft^3*d)	11.33	57030573.0	8147224.7

Much like the results of Table 5-3, the required volume and area are extremely high. This is especially true for the surface loading rate and the volumetric loading rate. This indicates that this design is not appropriate for this situation.

6.0 Selection of Final Design

6.1 Discussion of Preferred Alternative

Section 5.5 outlines each of three selected alternatives in terms of their resulting modeling values and will be discussed further to decide whether each design is feasible for the project.

6.1.1 Anaerobic CSTR

Regarding the anaerobic CSTR modeling results, it was found that the safety factor is lower than expected value of at least 5 [36]. In addition, the hydraulic retention time was calculated to be lower than one day which may provide an issue for solids separation within the system. When the HRT is low, the solids do not have enough time to separate from the liquid wastewater [38], making the BOD efficiency effectively lower than the expected efficiency of 80% [Table 4-2]. However, the anaerobic CSTR's modeling results proved to be effective at reducing the BOD and TKN efficiencies within the constrained volume.

6.1.2 Upflow Anaerobic Sludge Blanket

The UASB modeling results were calculated the same way as the UASB, meaning that all of the associated issues concerning the low safety factor and low HRT apply. The main difference with the UASB is sizing. Since the design height has previously been restricted to 8 feet, the UASB will not be feasible. It is required for a UASB that the height of the sludge bed should be at least 4.92 feet and an additional 3.28 feet is required for the gas solids liquid separator at the top of the design [39]. Additionally, UASB systems require constant monitoring by trained personnel. This monitoring is required as these systems have highly sensitive hydraulic and anaerobic conditions [6]. Sizing and maintenance create this technology highly difficult to manage and was therefore not selected for the final design.

6.1.3 Trickling Filter

The modeling indicated that the trickling filter design was unfeasible due to the extremely high surface loading and volumetric loading rates.

6.2 Selection of Preferred Alternative

Since the UASB and trickling filter designs were determined to be unfeasible for the project, the anaerobic CSTR was selected as the preferred alternative. However, since the modeling results, specifically the HRT, SRT, and safety factor, were determined to be inadequate, further steps were taken to model a recirculation flow rate that would increase the HRT, SRT, and safety factor to acceptable standards. The following section details the process of adding recirculation to the model design.

7.0 Unit Design

The design equations outlined in Section 5.3 defined the parameters required to achieve acceptable effluent concentrations. This method was appropriate in determining the feasibility with respect to each potential alternative. However, further analysis is required to fully define the anaerobic CSTR final design. Additional design parameters include the volume available, wastewater flow rate, and wastewater BOD concentration. Additional values from the literature and laboratory analysis provided inputs to determine reactor requirements and are detailed in the following subsections. Additionally, a clarifier was placed following the CSTR design to remove excess suspended solids and to provide the recirculation of wastewater and microbial populations to support a healthy microbial system within the CSTR over time.

7.1 Fixed Reactor Values

This section covers methods employed for the determination of reactor requirements and performance.

7.1.1 Given Operational Parameters and Sizing

The designed anaerobic CSTR was developed using maximum values provided by MRBC to ensure typical COC concentrations will be effectively treated to discharge requirements. Maximum values relevant to design included influent BOD concentration (S^0) and influent wastewater flow rate (Q^0). A conservative interior volume (V) of a 20’ x 8’ x 8’ shipping container was used. Values for each of these variables are shown in Table 7-1.

Table 7-1: Given Design Parameters

Variable	Description	Units	Value
S^0	Influent BOD	(mg BOD/L)	21075
Q^0	Influent Flow Rate	(gal/d)	8125
		(ft^3/day)	1086
		(L/d)	30757
V	Volume	(ft^3)	672
		(m^3)	19

Values highlighted in gray denote original values provided by MRBC. These original values have been converted to different units as appropriate for following calculations.

7.1.2 Constant Values for Microbial Kinetics

Values pertaining to microbial kinetics (Y, K, q, and b) are based upon definitions and values reported in Section 5.3. An additional variable (f_b) was required to determine the concentration of inert biomass within the system. This variable, f_b, is used to describe the fraction of biodegradable microorganisms that are formed as a product of active biomass digestion [36]. Additionally, f_b is a unitless variable that is relatively constant across different microorganisms. Values pertaining to these variables are shown in Table 7-2.

Table 7-2: Constant Values for Microbial Kinetics

Variable	Description	Units	Value
Y	Growth Yield Factor	(g VSS / g BOD)	0.091
K	Half Saturation Constant	(mg BOD_L/L)	10
q	Maximum Specific Rate of Substrate Utilization	(g BOD / g VSS*day)	8.4
b	Monod Decay Constant	(day^{-1})	0.02
f_d	Fraction Biomass that can be Oxidized During Decay	Unitless	0.8

7.1.3 Laboratory Values

Influent Inert Organic Suspended Solids (X_i^0) is a required input value. This variable describes the concentration of volatile suspended solids that are present within wastewater entering the system. Table 7-3 below shows the concentration of this variable as determined from laboratory testing (Section 3.2).

Table 7-3: Constant Values from Laboratory Testing

Variable	Description	Units	Value
X_i^0	Influent inert organic suspended solids	(mg VSS/L)	937

7.2 Calculated Reactor Values

Final design calculations were separated into five steps: hydraulic retention time, limiting variables, selected solids retention time, input active biomass, and reactor biomass constituents. These five steps are discussed in the following subsections.

7.2.1 Hydraulic Retention Time

As an influent wastewater flow rate and a fixed reactor volume has been given, the HRT has been determined using Equation 5-11, rearranging to solve for HRT (θ). The determined HRT is given in Table 7-4.

Table 7-4: Hydraulic Retention Time

Variable	Description	Units	Value
θ	Hydraulic Retention Time	(day)	0.62

7.2.2 Limiting Variables

A set of limiting variables are required in order to identify when the system will fail. These limiting variables include limiting substrate concentration (S_{min}), organism washout SRT, and limiting SRT $\left([\theta_x^{\min}]_{lim}\right)$.

Limiting substrate concentration was calculated using Equation 5-15. Organism washout SRT was calculated using Equation 5-14. Washout SRT communicates the point at which the system will begin to lose active biomass faster than it can produce it. Limiting SRT was calculated using Equation 7-1. Limiting SRT communicates the absolute minimum solids retention time required to sustain a steady state operation [36]. If the solids retention time falls below the value given by limiting SRT, the system be unable to rebuild a functional population of active biomass [36].

Equation 7-1: Limiting Solids Retention Time [36]

$$[\theta_x^{\min}]_{lim} = \frac{1}{Yq - b}$$

Input variables for this equation are found in Section 5.3. The resulting calculated values for these variables are shown in Table 7-5 below.

Table 7-5: Limiting Variables

Variable	Description	Units	Value
S_{min}	Limiting Substrate Concentration	(mg BOD_L/L)	0.27
θ_x^{min}	Organism Washout SRT	(day)	1.35
$[\theta_x^{min}]_{lim}$	Limiting SRT	(days)	1.35

7.2.3 Selected Solids Retention Time

Upon the determination of a limiting SRT, an operational SRT has been assumed. This selected SRT ($\theta_{x-selecte}$) was determined based on the selected safety factor (SF) for the system. A SF of 5 was selected as this would allow great resilience to variation in organic loading. This was deemed necissary as MRBC's wastewater experiences difference COC concentrations over time. That is, in the event MRBC produces a small BOD concentration on a given day, solids are retained long enough within the reactor to not effect future performance.

Using this selected SF, the assumed SRT was determined using a variation of Equation 5-13. Previously, this equation was utilized to determine the SF given an SRT and a limiting SRT. As a limiting SRT and SF are identified, this equation was rearranged to solve for the unknown variable, the selected SF. Equation 7-2 shows the modifications that have been made to the previous equation.

Equation 7-2: Selected Solids Retention Time [36]

$$\theta_{x-selected} = SF_{selected} * [\theta_x^{\min}]_{lim}$$

Where:

$\theta_{x-selected}$ = Selected SRT
$SF_{selected}$ = Safety Factor of Basin (unitless)
$[\theta_x^{\min}]_{lim}$ = Limiting Solids Retention Time (days)

Values corresponding to these two variables are shown in Table 7-6.

Table 7-6: Selected Solids Retention Time

Variable	Description	Units	Value
$SF_{selected}$	Selected Saftey Factor	(unitless)	5.00
$\theta_{x\text{-selected}}$	Selected SRT	(day)	6.75

7.2.4 Input Active Biomass

CSTRs are steady state processing units. That is, the flow entering the reactor must equal the flow coming out of the reactor. This steady flow out of the reactor includes the constituent concentrations present at any point within the reactor. Flow entering the reactor is assumed to have no active biomass that would digest COCs. Given this, if there is no biomass introduced entering the reactor, it would quickly dilute the biomass concentration until there is none remaining within the reactor. Therefore, it is important that active biomass is introduced from recycling settled solids exiting the downstream clarifier. The following equations compute the input active biomass concentration (X_a^1) that is required to operate the CSTR at the previously selected SRT. These equations are heavily reliant on microbial kinetics that provide the rate at which biomass is produced and destroyed. Each equation described below is in the order of operation with each successive result dependent upon the previous.

The reactor effluent substrate (S^e) gives the concentration of BOD that would theoretically discharge from the CSTR. It is important to note that this is a theoretical value and is what would be expected from a treatment system under perfect conditions. Therefore, it is highly likely that the true value of effluent substrate will be greater than the theoretical value. This value is determined using Equation 7-3.

Equation 7- 3: Reactor Effluent Substrate [36]

$$S^e = K\frac{1+b\theta_x}{Y\hat{q}\theta_x-(1+b\theta_x)}$$

The reactor active biomass (X_a) gives the concentration of active biomass required to support the design HRT and SRT given substrate (BOD) influent and effluent concentrations. This value is determined using Equation 7-4.

Equation 7- 4: Reactor Active Biomass [36]

$$X_a = \frac{\theta_x}{\theta}\left(\frac{Y\,(S^0-S^e)}{1+b\theta_x}\right)$$

The input active biomass (X_a^1) gives the concentration of active biomass that must be added to the stream entering the CSTR. This is critical because it supports the overall health and performance of the reactor. Input active biomass (X_a^1) is determined using Equation 7-5.

Equation 7-5: Input Active Biomass [36]

$$X_a^1 = \left(1-\frac{\theta}{\theta_x}\right)X_a$$

The calculated values determined for these variables is shown in Table 7-7.

Table 7-7: Input Active Biomass

Variable	Description	Units	Value
S^e	Reactor Effluent Substrate	(mg/L)	2.84
X_a	Reactor Active Biomass	(mg VSS/L)	18344
X_a^1	Input Active Biomass	(mg VSS/L)	16663

7.2.5 Reactor Biomass Constituents

With reactor active biomass (X_a) determined, the next step is to determine the concentration of reactor inert biomass (X_i) and thereby the reactor total biological solids (X_v) leaving the reactor. This value is used with the efficiency of the settling tank to determine how much TSS would theoretically be discharged into municipal sewers.

Reactor inert biomass describes the concentration of inactive biomass. This material is comprised of biological waste produced by active biomass in addition to dead biomass. This value is determined by Equation 7-6.

Equation 7-6: Reactor Inert Biomass [36]

$$X_i = \frac{\theta_x}{\theta}[X_i^0] + X_a(1 - f_d)b\theta_x$$

Where:

X_i^a = Influent Inert Biomass
f_d = Fraction of Biomass that can be Oxidized During Decay

Reactor total biological solids is the sum of both reactor active biomass (X_a) and reactor inert biomass (X_i).

A known value, the ratio of the concentration of reactor inert biomass (X_i) to reactor active biomass (X_a) is used in mass balance equations to convert known active biomass concentrations to an inert biomass concentration.

Computed values for these variables are shown in Table 7-8.

Table 7-8: Reactor Biomass Constituents

Variable	Description	Units	Value
X_a	Reactor active biomass	(mg VSS/L)	18344
X_i	Reactor inert biomass	(mg VSS/L)	10722
X_v	Reactor total biological solids	(mg VSS/L)	29065
	Ratio active biomass to inert biomass	(mg VSS_i / mg VSS_a)	0.58

Excel work accompanying these calculations can be found in Appendix F.

7.3 Mass Balance

A mass balance of the system was completed to determine flow throughout the system. These calculations were completed over three iterations. These iterations included the assumption that the clarifier would possess a 97% efficiency in settling solids.

The first mass balance iteration determined mass rates assuming no return stream coming from the clarifier. A second iteration was created now considering a return stream. The mass rate of return stream must equal the mass rate entering the CSTR. As such, the return mass rate was determined. Finally, a third iteration was completed to balance all flows and active biomass concentrations according to previously determined mass rates. A table of each successive calculations has been provided in Appendix G.

The mass balance of system recirculation has been completed only considering active biomass concentrations (X_a). This has been done as active biomass is the only critical factor within return flow. The CSTR must receive an input of active biomass as communicated in Table 7-7. An additional note within this mass balance is the requirement that return active biomass concentration must be equal to the concentration present within the waste stream.

An illustration of this mass balance is provided in Figure 7-1.

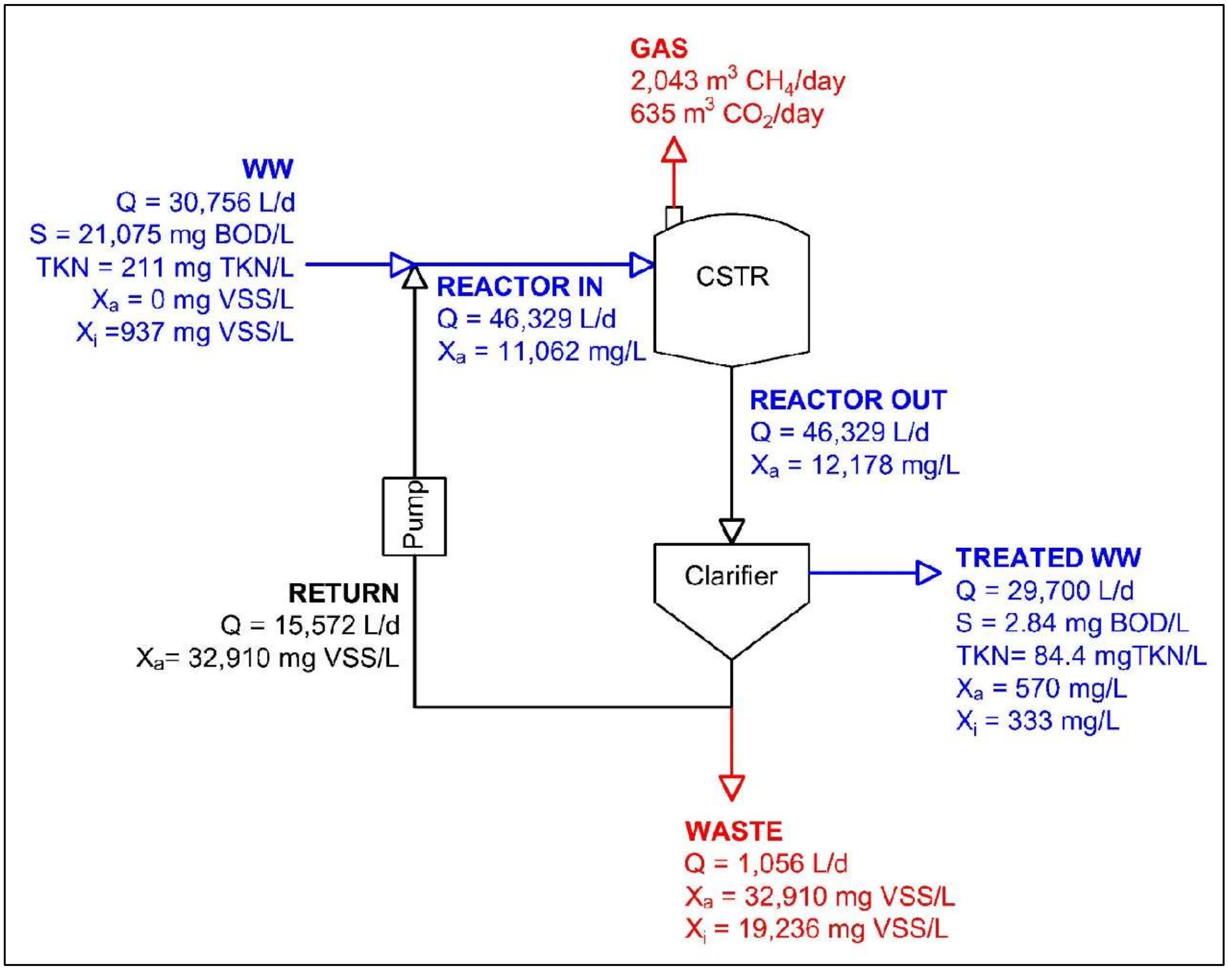

Figure 7-1: Mass Balance Summary

The concentrations for each COC have been provided for each stream exiting the system. Treated wastewater is the stream discharging to municipal sewer. Figure 7-1 shows that this stream shall have a BOD concentration of 2.83 mg/L, a TKN concentration of 84.4 mg/L and a VSS concentrations of 903 mg/L. Each of these COC concentrations fall below the City of Flagstaff's discharge standard communicated in Table 1-1.

This system produces high volumes of methane (2,053 m^3 CH$_4$/day). It is highly recommended that this greenhouse gas is somehow managed. Potential options to hand this gas byproduct shall be outlined in Section 6.8. There is also a substantial production of carbon dioxide (635 m^3 CO$_2$/day). This gas should additional be subject to handling. Although, handling options for carbon dioxide would be dependent on methane handling. As such, recommendations for CO$_2$ handling shall not be outlined.

Detail regarding settling tank design shall be limited to the HRT communicated in Table 7-4 and the assumption of a 97% efficiency. The team has determined that it is safe to assume a healthy biomass shall settle out of solution within the calculated HRT of 0.62 days. As the system is steady state, this HRT regarding the CSTR shall translate to the settling tank.

Means to provide additional details to clarifier design would include the development and testing of reactor biomass. These procedures are not within the capacity of the design team. As such, the team has only detailed that the settler must have an efficiency of 97%.

7.4 Material Selection

It has been recommended that stainless steel will work best for the project. Anaerobic processes have the tendency to corrode their enclosure and stainless steel is corrosion resistant [40]. In addition, stainless steel being corrosion resistant, it is also a high-quality material and has been proven to be reliable in the environmental engineering sector [40].

MRBC has communicated that they have a team that works on all in piping in house. With this information, the design team shall give MRBC full control over pipe design.

There are options for potential settling tank materials. These options include stainless steel or plastic. The team intends this design to be highly resilient and therefore recommends stainless steel for the settling tank. Although, as mentioned settling tank design shall not be detailed by the design team. This material selection acts as a recommendation and shall be used to the cost appraisal of the project in Table 7-9.

7.5 Final Design

The final design of the pretreatment process follows the CSTR system as shown in Figure 7-1. The operational volume of the CSTR is 672 ft^2 as shown in Table 7-1. This volume will take up most of the volume available within a standard 8' x 8' x 20' shipping container. An additional shipping container is therefore required to contain the design settling tank. This amendment to project constraints has been approved by MRBC and will be included within drawings of the final design.

Drawings of the system within two stacked shipping containers are provided in Figures 7-2, 7-3 and 7-4. Dimensions in each of these drawings are in feet.

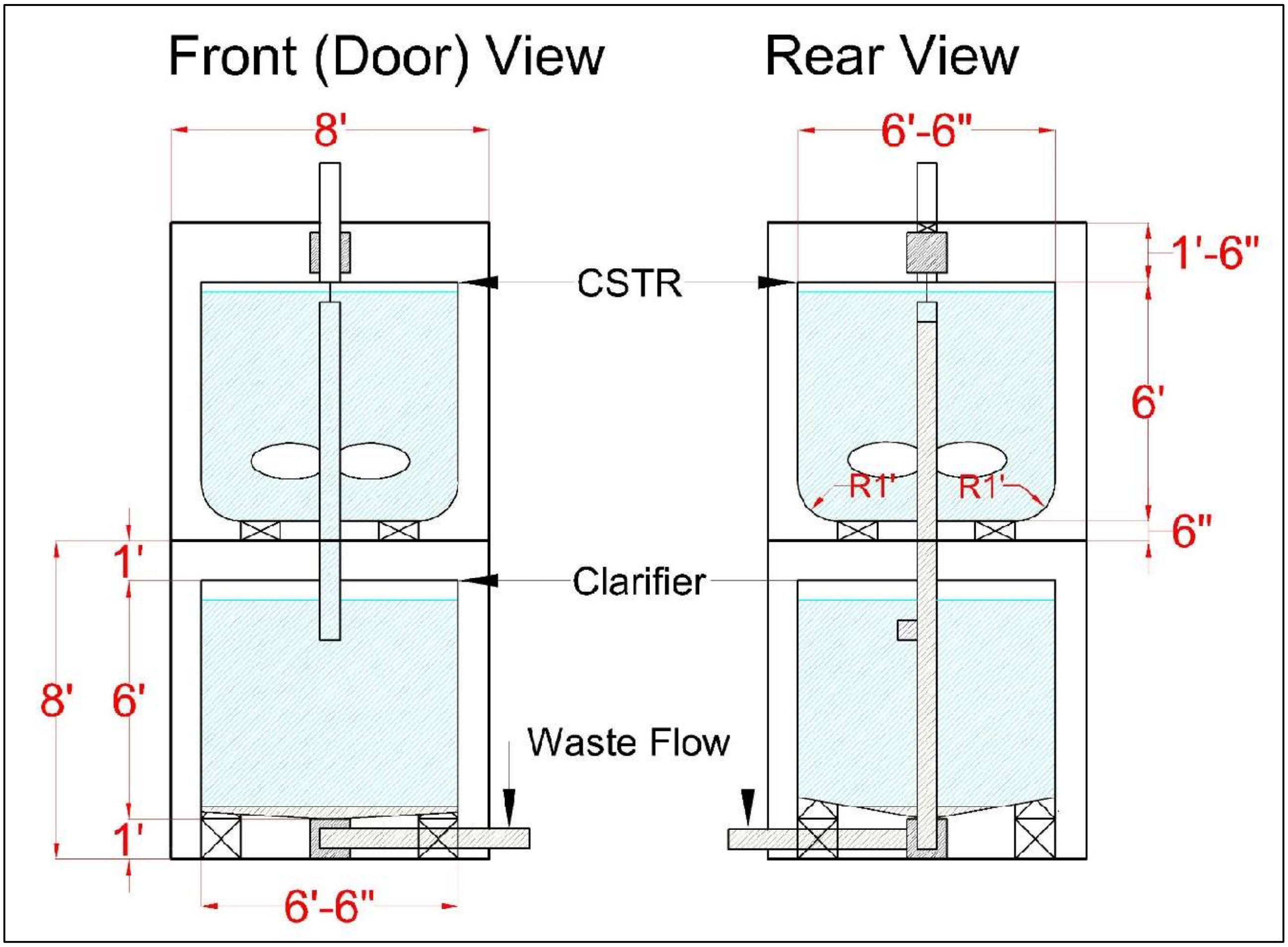

Figure 7-2: Unit Design Front and Back View (Inside)

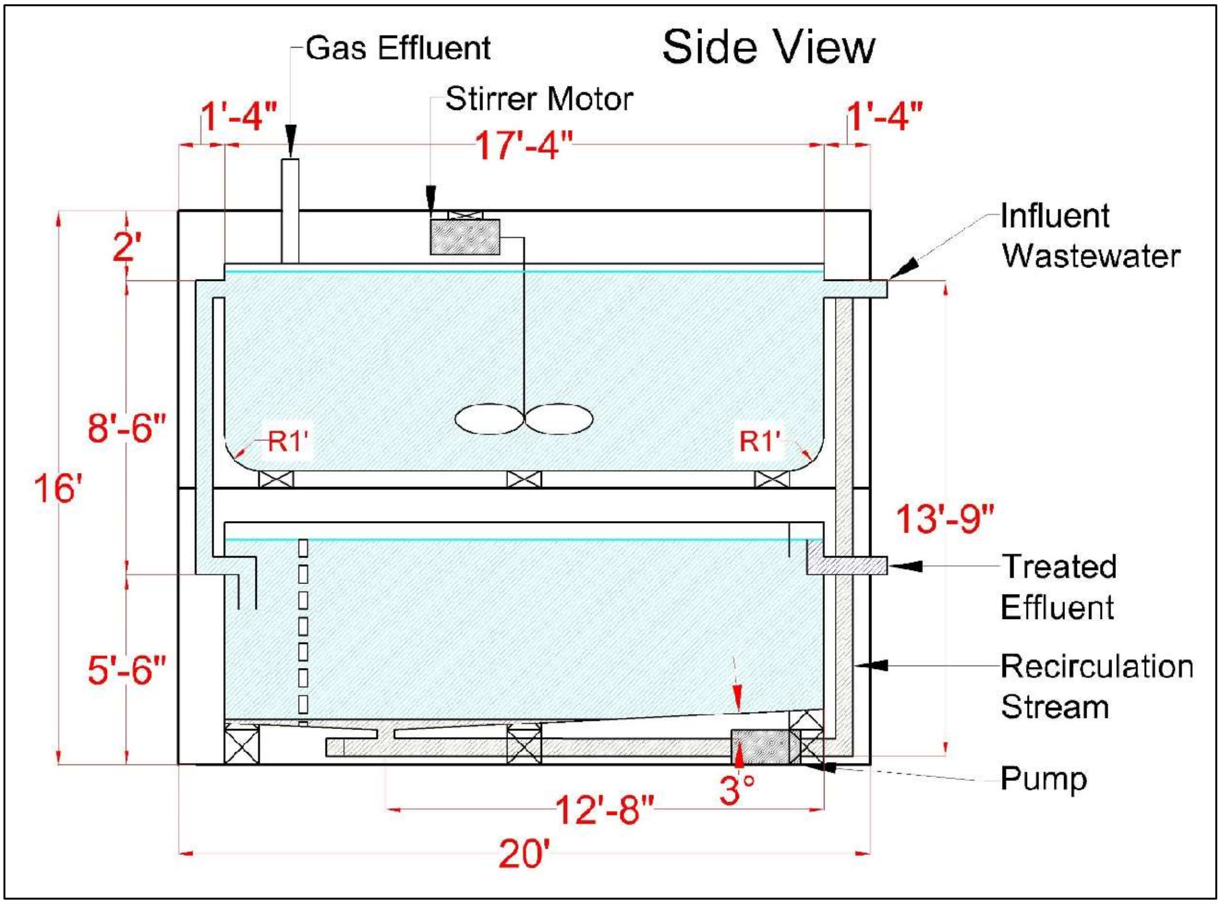

Figure 7-3: Unit Design Side View (Inside)

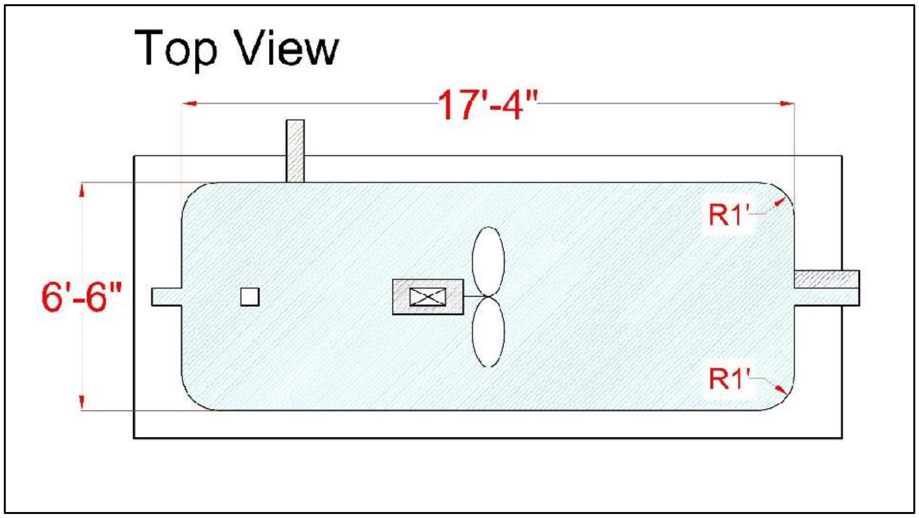

Figure 7-4: Unit Design Top View (Inside)

The top view of the system does not include a view of the settling tank below. This is due to the settling tank having the same footprint as the CSTR placed above.

Designs of the view from outside the shipping containers have additionally been provided in Figures 7-5, 7-6, and 7-7. These have been provided as they include additional dimensions more easily seen via this format.

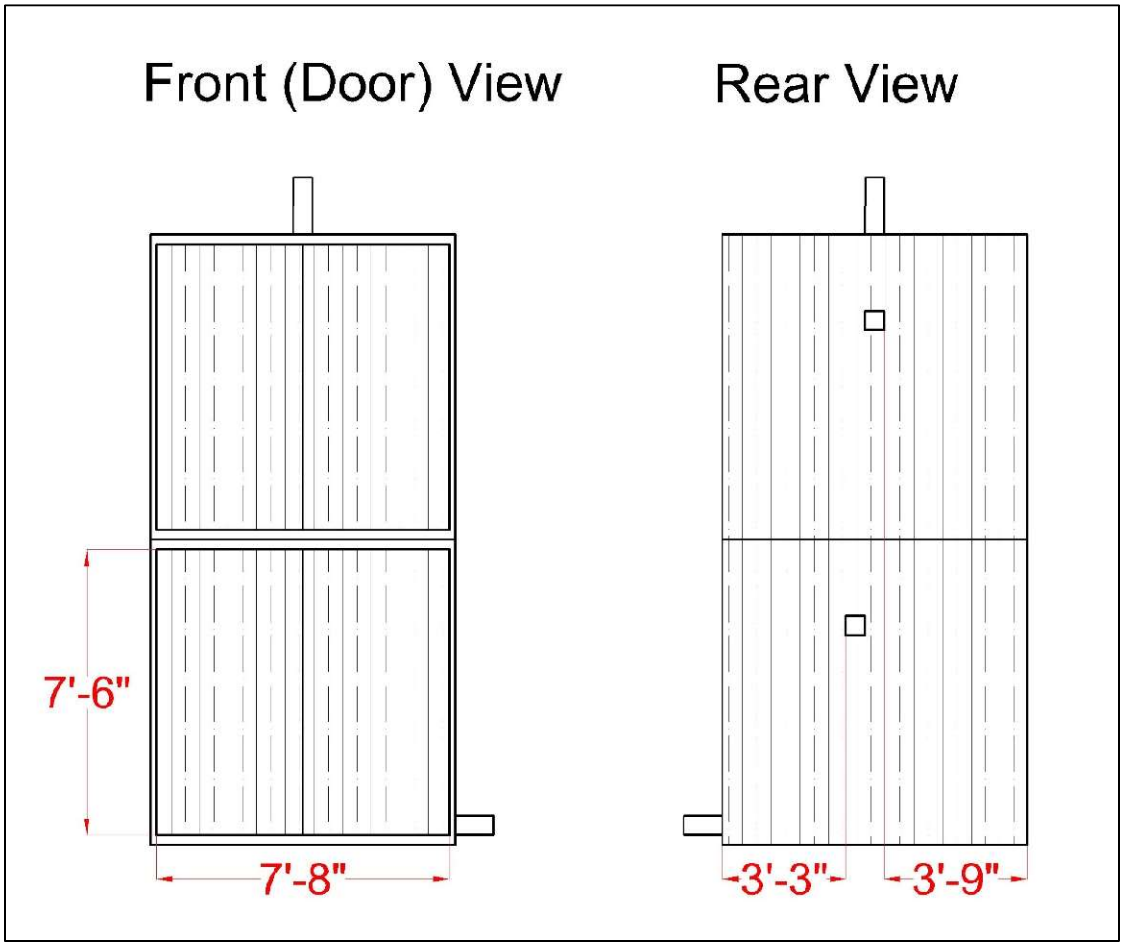

Figure 7-5: Unit Design Front and Back View (Outside)

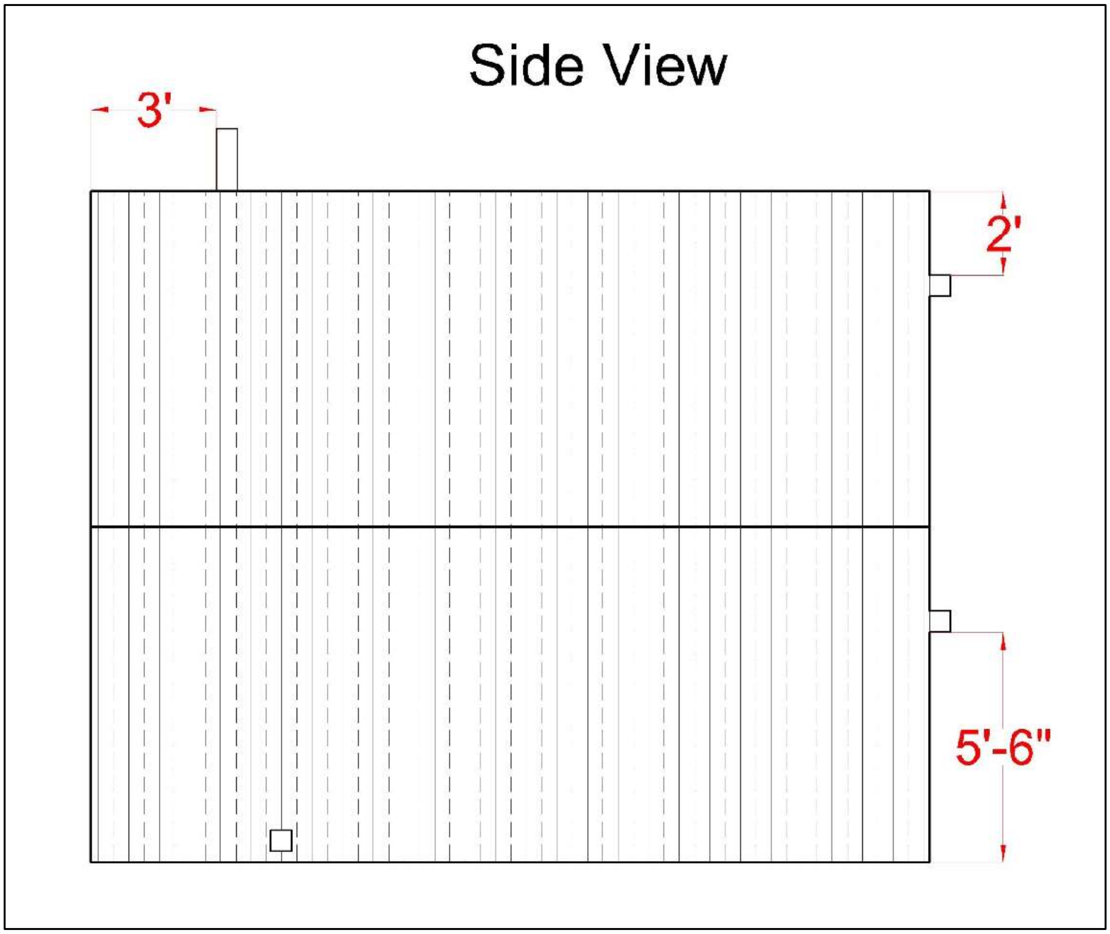

Figure 7-6: Unit Design Side View (Outside)

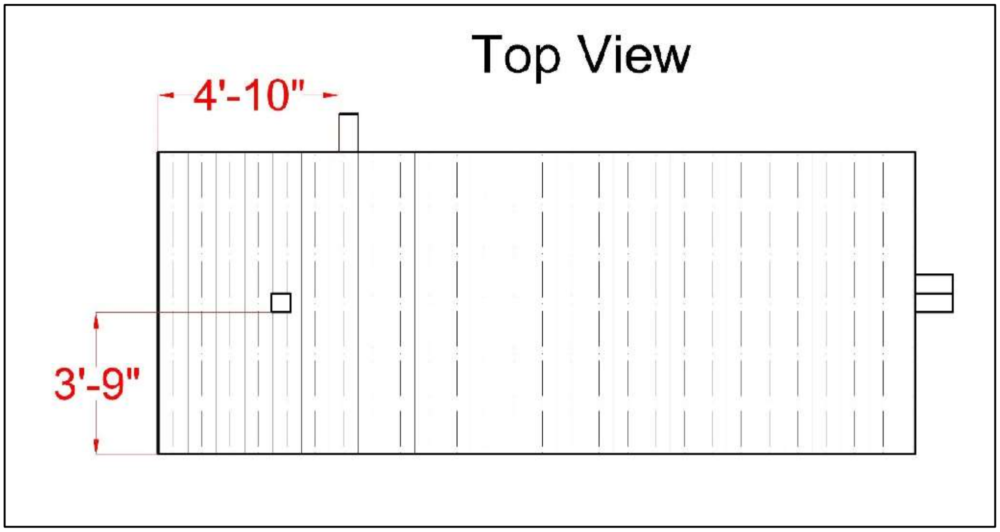

Figure 7-7: Unit Design Top View (Outside)

7.6 Cost of Design Implementation

The cost of design implementation has been outlined in Table 10-3. This table references the researched capital and installation costs as outlined in Table 4-2. The maximum dollar amount for these technologies was selected for use in this table. This is due to the selected stainless-steel material being more expensive than standard plastic or steel tanks. It should additionally be noted that the clarifier cost within this table may be less than the actual cost of implementation as the upper end of the range was used in calculations and since the clarifier was not design due to a lack of given information, a true cost estimate could not be calculated. Since these costs are estimated, the design implementation subtotal has been determined to be a liberal estimate of the total cost.

Table 7-9: Cost of Design Implementation

Cost of Design Implementation	
Settling Tank [41]	$35,000.00
Continuously Stirred Tank Reactor [29]	$25,000.00
Design Implementation Subtotal	**$60,000.00**

7.7 Gas Byproduct Handling Options

Since anaerobic processes produce methane and carbon dioxide as harmful greenhouse gases, the gases must be captured and handled properly. The team has come up with two potential options for capture of these byproducts. These options have been detailed below:

7.7.1 Flaring

The first option for the mitigation of uncontrolled release is flaring. Flaring is the process of burning off gases to convert those gases to carbon dioxide. Although carbon dioxide is released during the process, flaring only contributes to about 1% of carbon dioxide release into the atmosphere [42]. In addition, methane has a higher potential for global warming than carbon dioxide does, so converting the methane to carbon dioxide will reduce the harm of emissions [42]. This option would entail placing a flare stack on top of the shipping container that would capture the methane and burn it as it reaches the top. A flare stack costs about $3,000 [43] and would produce a net economic savings of zero since the gas is burned off and is not reused.

7.7.2 Cogeneration

Cogeneration, also known as combined heat and power (CHP) produces mechanical and thermal energy. Methane is introduced as the fuel and goes into a gas turbine [44]. The blades in the gas turbine spin a generator that produces electricity using mechanical energy [45]. The produced electricity can be used to power the pre-treatment system which can save MRBC money. The gas turbine also produces heat [44] which can be used to heat the pre-treatment system in the winter months which can also provide economic savings. Using a typical electricity cost in Flagstaff, AZ of $0.16 kWh [46], the estimated methane production of 8.46×10^5 kW/day was used to calculate the daily economic savings on electricity from this option. The daily savings were estimated to be about $3,250. With that being said, the installation cost of the gas turbine, generator, and heat system can range anywhere from $2,683/kW to $6,200/kW [47]. With a methane production of 846 kW per day, the installation cost would range from $2.2 million to $5.2 million. Although the installation cost is high, with the estimated $3,250/day savings, the installation cost would be paid back within two to four years. After breaking even, the daily savings would be a net gain.

8.0 Impact Analysis

The primary benefit of this project is the immediate treatment of wastewater before it gets transferred to the wastewater treatment plant (WWTP). This will help the WWTP improve their efficiency and reduce their repair and maintenance costs as they will no longer need to worry about MRBC's wastewater interfering with the microbial balance within the facility. This reduction of contaminants will lead to MRBC's economic savings because they will no longer be receiving fines from the City of Flagstaff for being out of compliance with the pretreatment standards. Also in terms of economic value, methane production from the anaerobic process can be used to generate electricity if captured properly. The excess sludge is extremely nutrient rich and can be used to fertilize crops and can be introduced into MRBC's existing solid waste stream that gets transported to a local farm which supports local business. Methane and sludge reuse represent environmentally sustainable practices which can encourage other local businesses to also enact sustainable practices.

Implementation of this project incurs extra financial costs for MRBC. These costs include maintenance and construction of the treatment system as well as extra electricity costs. However, these values should still be less than the accumulating monthly fine that MRBC currently faces. There is also a cost associated with the transport of the sludge to the farm. Any methane that is not used for energy production or completely burned off will be released into the environment which may increase the effects of climate change. The methane and sludge production can also produce an unpleasant odor for the production facility's neighbors. While there are some industrial odors in the area, the nearby supply store and motorcycle shop's economic business could be negatively affected if the odor is too potent. The odor can also travel downwind and workers at MRBC will also be affected. However, the smell can be mitigated using odor control measures, and the neighbors are not extremely close to the facility.

Table 8-1: Impact Analysis

Pros	**Cons**
Eliminates monthly fines from the city	Cost of increased electricity usage
Reducing COC limits to acceptable levels helps the WWTP's operability	Difficulty/expense of handling of methane byproduct
Possibility of energy production using methane	Production of sludge may cause a poor odor
Sludge production from the CSTR and settling tank can be used as fertilizer by a local farm in addition to existing side stream	Cost of maintenance and construction/materials
Promote sustainable local business	

9.0 Summary of Engineering Work

A summary of engineering work performed is summarized in Table 9-1**.** This table reports on logged hours with respect to positions; senior engineer (SE), project engineer (PE), engineer in training (EIT), and lab technician (LAB). Reported hours are compared to the hours that have been budgeted for each position in the project proposal. Finally, a percentage of hours worked to budgeted hours has been provided to easily compare the use of budgeted hours.

Table 9-1: Summary of Engineering Work

Summary of Engineering Work					
Description	**Senior Engineer**	**Project Engineer**	**EIT**	**Lab**	**Total**
Current Hours	60	147	156	56	**418**
Total Budgeted Hours	61	169	183	61	**474**
Running Percentage of Budgeted Hours	98%	87%	85%	92%	**88%**

A value of 88% use of the budgeted hours indicates proper time management throughout the project and that resources were properly utilized, ensuring the success of the project overall.

10.0 Summary of Engineering Costs

10.1 Cost of Personnel

The cost of personnel is detailed in Table 10-1. Specifically, this table calculates a dollar amount per position considering hours used, and cost per hour. Hours used communicated within this table have been determined from Table 9-1.

Table 10-1: Cost of Personnel

Cost of Personnel			
Position	**Hours**	**Dollars/Hour**	**Dollars**
Senior Engineer	60	218	$13,026
Project Engineer	147	134	$19,665
Engineer in Training	156	94	$14,617
Lab Technician	56	68	$3,808
Personnel Subtotal			**$51,115**
Proposal Estimation			**$57,061**

This table shows that the cost of personnel comes to a subtotal of approximately $51,115. Comparing this to the proposal's estimation of $57,061 shows that the cost of personnel fell 10% below the estimated value.

10.2 Cost of Laboratory Analysis

The cost of laboratory analysis is shown in Table 10-2. This table calculates costs according to materials used. Subsections within this table break down costs according to non-consumable and consumable items. Consumable items relate to testing materials used to determine COC concentrations.

Table 10-2: Actual Cost of Laboratory Analysis

Cost of Laboratory Analysis			
Non-Consumable Items			
Item	**Units**	**Dollars/Unit**	**Dollars**
NAU EnE Lab Rental (Days)	24	$100.00	$2,400
Lab PPE (Coat, Eye Pro., Gloves)	4	$50.00	$200
Non-Consumable Subtotal			**$2,600**
Consumable Items			
Item	**Cost/Test**	**# of Tests**	**Total Cost**
Calcium Chloride	$0.06	19	$1.07
Ferric Chloride	$0.03	19	$0.52
Phosphate Buffer	$0.06	19	$1.21
Magnesium Sulfate	$0.05	19	$0.91
COD, Low Range, 3-150 mg/L	$3.37	6	$20.19
COD, High Range, 20-1500 mg/L	$3.32	6	$19.89
COD, High Range Plus, 200-15,000 mg/L	$3.32	6	$19.90
PhosVer 3 Phosphate Reagent Powder Pillow	$0.77	4	$3.07
Nitrogen Reagent Set	$1.18	0	$0.00
Filter Disk, glass fiber, 47mm	$0.59	6	$3.55
Simplified TKN (TNTPlus Vial Test)	$8.80	4	$35.20
Consumable Subtotal			**$106**
Laboratory Analysis Subtotal			**$2,706**
Proposal Estimation			**$4,519**

This table shows that the cost of laboratory analysis comes to a subtotal of $2,706. Comparing this to the proposal's estimation of $4,519 shows that the cost of laboratory analysis fell 40% below the estimated value.

10.3 Total Cost of Engineering Services

Subtotals that have been determined from previous subsections are shown in Table 10-4.

Table 10-3: Total Cost of Engineering Services

Total Cost of Engineering Services	
Personnel Subtotal	**$51,115**
Laboratory Analysis Subtotal	**$2,706**
Design Implementation Subtotal	**$60,000**
Total	**$113,821**
Proposal Estimation	**$121,580**

This table shows that the total cost of the project comes to a grand total of $113,821. Comparing this to the proposal's estimation of $121,580 shows that the total project cost fell 6% below the estimated value.

11.0 Conclusion

The chosen design is reliable, easy to maintenance, and relatively inexpensive to implement at the MRBC facility. The total cost for the project has been calculated at approximately $98,175 which is about $334,000 below the prescribed budget of $432,000. Additionally, the 6' x 7' x 16' CSTR volume fits within the allowed shipping container volume of 8' x 8' x 20'. The 6' x 7' x 16' clarifier also fits within the additional allowed container volume of 8' x 8' x 20'. The major impact of the project is the removal of contaminants of concern in the wastewater which will lower MRBC's monthly fines, effectively offsetting the cost of the treatment system over time. Although the design has been proven to be effective in lowering BOD and TKN concentrations, the anaerobic CSTR may produce methane as a result. This methane production may be captured and used for energy production if MRBC chooses to do such and is recommended as it will save them money over time and is a sustainable business practice. In conclusion, the selected final design has been proven to be efficient in reduction of the major COCs, is under budget, and is within the allowable size constraint.

12.0 References

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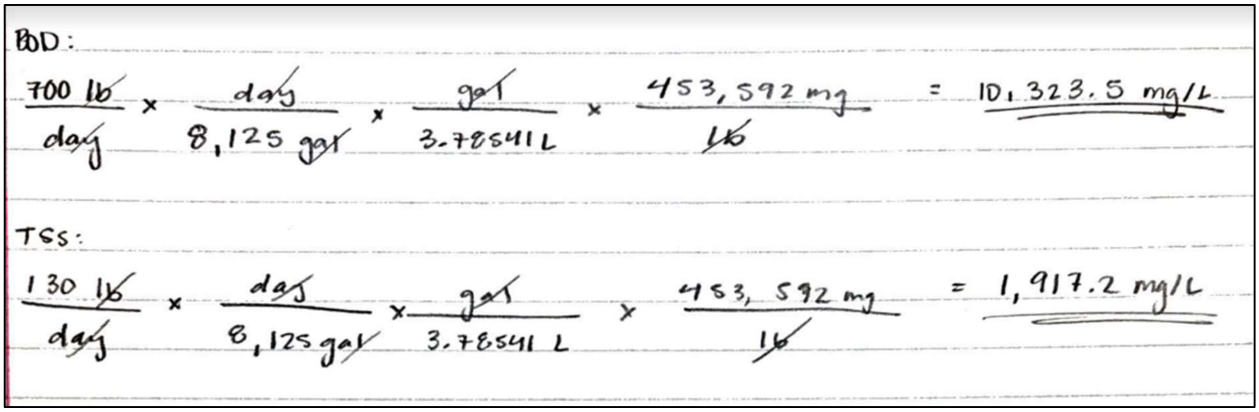
Appendices

Appendix A: Sample Calculations



BOD:

$$\frac{700\ \cancel{lb}}{\cancel{day}} \times \frac{\cancel{day}}{8{,}125\ \cancel{gal}} \times \frac{\cancel{gal}}{3.78541\ L} \times \frac{453{,}592\ mg}{\cancel{lb}} = \underline{\underline{10{,}323.5\ mg/L}}$$

TSS:

$$\frac{130\ \cancel{lb}}{\cancel{day}} \times \frac{\cancel{day}}{8{,}125\ \cancel{gal}} \times \frac{\cancel{gal}}{3.78541\ L} \times \frac{453{,}592\ mg}{\cancel{lb}} = \underline{\underline{1{,}917.2\ mg/L}}$$

Figure A-1: BOD and TSS Permit Sample Calculations

Appendix B: Lab Testing Results Excel Calculations

Table B-1: Lab Results Excel Calculations

BOD:

BOD (mg/L)	Rejected BOD (mg/L)
1960	
387	
125	

Stats	
AVG	824
STD.DEV	811
Median	387

COD:

Undiluted Concentrations (mg/L)	**Rejected Undiluted Concentrations (mg/L)**
14916	
13530	
	74122
2184	

Stats	
AVG	10210
STD.DEV	5703
Median	13530

Calculated Dilution Factors	
1:10 DF	**1:100 DF**
11	98

Phosphate:

Undiluted Concentrations (mg/L PO4)	**Rejected Undiluted Concentrations (mg/L PO4)**
4.64	
7.04	
3.04	
5.62	

Stats	
AVG	5.09
STD.DEV	1.46
Median	5.13

TSS:

TSS (mg/L)	**Rejected TSS (mg/L)**
	3304
1020	
360	

Stats	
AVG	690
STD.DEV	330
Median	690

VSS:

VSS (mg/L)	**Rejected VSS (mg/L)**
	1310
937	
323	

Stats	
AVG	630
STD.DEV	307
Median	630

TKN:

TKN (mg/L)	**Rejected TKN (mg/L)**
113	

Appendix C: Model Input Values

Table C-1: Microbial Input Values

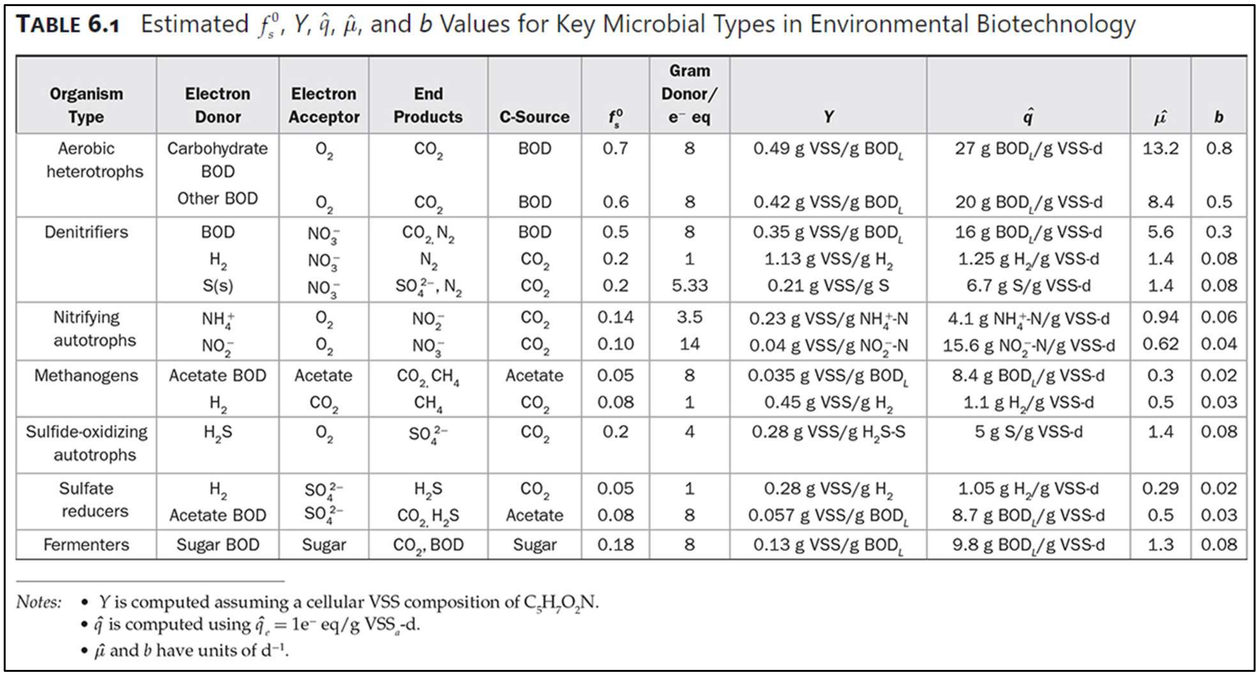


TABLE 6.1 Estimated f_s^0, Y, $\hat{q}$, $\hat{\mu}$, and b Values for Key Microbial Types in Environmental Biotechnology

Organism Type	Electron Donor	Electron Acceptor	End Products	C-Source	f_s^0	Gram Donor/ e^- eq	Y	$\hat{q}$	$\hat{\mu}$	b
Aerobic heterotrophs	Carbohydrate BOD	O_2	CO_2	BOD	0.7	8	0.49 g VSS/g BOD_L	27 g BOD_L/g VSS-d	13.2	0.8
	Other BOD	O_2	CO_2	BOD	0.6	8	0.42 g VSS/g BOD_L	20 g BOD_L/g VSS-d	8.4	0.5
Denitrifiers	BOD	NO_3^-	CO_2, N_2	BOD	0.5	8	0.35 g VSS/g BOD_L	16 g BOD_L/g VSS-d	5.6	0.3
	H_2	NO_3^-	N_2	CO_2	0.2	1	1.13 g VSS/g H_2	1.25 g H_2/g VSS-d	1.4	0.08
	S(s)	NO_3^-	SO_4^{2-}, N_2	CO_2	0.2	5.33	0.21 g VSS/g S	6.7 g S/g VSS-d	1.4	0.08
Nitrifying autotrophs	NH_4^+	O_2	NO_2^-	CO_2	0.14	3.5	0.23 g VSS/g NH_4^+-N	4.1 g NH_4^+-N/g VSS-d	0.94	0.06
	NO_2^-	O_2	NO_3^-	CO_2	0.10	14	0.04 g VSS/g NO_2^--N	15.6 g NO_2^--N/g VSS-d	0.62	0.04
Methanogens	Acetate BOD	Acetate	CO_2, CH_4	Acetate	0.05	8	0.035 g VSS/g BOD_L	8.4 g BOD_L/g VSS-d	0.3	0.02
	H_2	CO_2	CH_4	CO_2	0.08	1	0.45 g VSS/g H_2	1.1 g H_2/g VSS-d	0.5	0.03
Sulfide-oxidizing autotrophs	H_2S	O_2	SO_4^{2-}	CO_2	0.2	4	0.28 g VSS/g H_2S-S	5 g S/g VSS-d	1.4	0.08
Sulfate reducers	H_2	SO_4^{2-}	H_2S	CO_2	0.05	1	0.28 g VSS/g H_2	1.05 g H_2/g VSS-d	0.29	0.02
	Acetate BOD	SO_4^{2-}	CO_2, H_2S	Acetate	0.08	8	0.057 g VSS/g BOD_L	8.7 g BOD_L/g VSS-d	0.5	0.03
Fermenters	Sugar BOD	Sugar	CO_2, BOD	Sugar	0.18	8	0.13 g VSS/g BOD_L	9.8 g BOD_L/g VSS-d	1.3	0.08

Notes:
- Y is computed assuming a cellular VSS composition of $C_5H_7O_2N$.
- $\hat{q}$ is computed using $\hat{q}_e = 1e^-$ eq/g VSS_a-d.
- $\hat{\mu}$ and b have units of d^{-1}.

Appendix D: Anaerobic System Excel Calculations

Table D-1: Anaerobic System Excel Sample Calculations

Given			
Influent BOD (S_0) (mg/L)	21000	g/L	594.9008
Effluent BOD (S) (mg/L)	10323	g/L	292.4363
Growth Yield (Y) gVSs/gBOD	0.45	gVSs/gBOD	0.45
Cell Concentration (X)	1000		1000
Cell Death Rate (b) /d	0.03	/d	0.03
Flow Rate (Q) (gal/d)	8125	ft^3/d	1086.158
Half-Saturation Constant (k_s) (mg/L)	10	g/L	0.283286
Maximum Specific Rate of Substrate Utilization (q) gBod/ (gVSs*d)	1.1	gBod/ (gVSs*d)	1.1

Table D-2: Anaerobic System Excel Sample Calculations (Continued)

Calculated	
Parameter	**Value**
Hydraulic Retention Time (θ) (d)	0.275
Volume ($\forall$) (ft^3)	299
Solids Retention Time (θ_x) (d)	2.15
Minimum Allowable Cell Residence Time ($\theta_{c\text{-}min}$)	2.15
Safety Factor (SF)	1.00
S_{min}	0.018

Appendix E: Trickling Filter Excel Calculations

Table E-1: Trickling Filter Excel Sample Calculations

Square Trickling Filter			
Parameter	Value	Parameter	Value
Q (gal/d)	8125	Q (ft^3/d)	1086.158
Q_r (gal/d)	7480	Q_r (ft^3/d)	1000
A_{pv} (ft^2)	96	A_{pv} (ft^2)	96
L (ft)	16	L (ft)	16
W (ft)	6	W (ft)	6
D (ft)	7	D (ft)	7
a (/m)	200	a (/ft)	60.97561
S_0 (mg/L)	21000	S_0 (mg/ft^3)	594900.8

Table E-2: Trickling Filter Excel Sample Calculations (Continued)

Determined area	
HL (ft/d)	131.2
SL mg/(ft^2*d)	654.2
VL mg/(ft^3*d)	11.33

Table E-3: Trickling Filter Excel Sample Calculations

A_{pv} (ft^2)	8.278644245	V (ft^3)	57.95050972
V (ft^3)	16198.3565	A_{pv} (ft^2)	2314.050929
V (ft^3)	57030572.96	A_{pv} (ft^2)	8147224.709

Appendix F: Reactor Biomass Constituent Calculations

Table F-1: Reactor Biomass Calculations

Step 1: Find Hydraulic Retention Time			
Variable	**Description**	**Units**	**Value**
θ	Hydraulic Retention Time	(day)	0.62
Step 2: Find S_{min}, $[\theta_x^{min}]_{lim}$, and θ_x^{min}			
Variable	**Description**	**Units**	**Value**
S_{min}	Limiting Substrate Concentration	(mg BOD/L)	0.27
θ_x^{min}	Organism Washout SRT	(day)	1.35
$[\theta_x^{min}]_{lim}$	Limiting SRT	(days)	1.35
Step 3: Set a Solids Retention Time WRT SF			
Variable	**Description**	**Units**	**Value**
$SF_{selected}$	Input Saftey Factor	(unitless)	5.00
$\theta_{x\text{-}selected}$	Selected SRT	(day)	6.75
Step 4: Calculate Input Active Biomass (X_a^0)			
Variable	**Description**	**Units**	**Value**
S^e	Reactor Effluent Substrate	(mg/L)	2.84
X_a	Reactor Active Biomass	(mg VSS/L)	18344
X_a^1	Input Active Biomass	(mg VSS/L)	16663
Step 5: Calculate Conc. Of Active, Inert, and Total Vol Solids			
Variable	**Description**	**Units**	**Value**
X_a	Reactor active biomass	(mg VSS/L)	18344
X_i	Reactor inert biomass	(mg VSS/L)	10722
X_v	Reactor total biological solids	(mg VSS/L)	29065
-	Ratio active biomass to inert biomass	(mg VSS_i / mg VSS_a)	0.58

Appendix G: Mass Balance

Table G-1: Mass Balance Calculations

Iteration 1: Assume No Return Flow			
Step 1: Calculate Mass Rates			
Variable	**Description**	**Units**	**Value**
m_a^1	WW Influent Active Mass Rate	(mg/d)	0.00E+00
m_a^2	CSTR Influent Active Mass Rate	(mg/d)	5.12E+08
m_a^3	CSTR Effluent Active Mass Rate	(mg/d)	5.64E+08
m_a^4	Effluent WW Active Mass Rate	(mg/d)	1.69E+07
m_a^5	Settled Active Mass Rate	(mg/d)	5.47E+08
Iteration 2: Assume Mass Rate CSTR Influent = Mass Rate Return			
Step 1: Calculate Remining Mass Rates			
Variable	**Description**	**Units**	**Value**
m_a^7	Return Active Mass Rate	(mg/d)	5.12E+08
m_a^6	Waste Active Mass Rate	(mg/d)	3.48E+07

Table G-2: Mass Balance Calculations Continued

Iteration 3: Balance Flow and Concentration by Iterating				
Step 1: Given All Mass Rates, Balance Flow & Active Concentration				
Location	**Variable**	**Description**	**Units**	**Value**
1	m_a^1	WW Influent Active Mass Rate	(mg/d)	0.00E+00
	Q^1	Influent Flow Rate	(L/d)	30757
	X_a^1	Influent Active Biomass	(mg/L)	0
	$m_a^{1\text{-CHECK}}$	CHECK WW Influent Active Mass Rate	(mg/d)	0
2	m_a^2	CSTR Influent Active Mass Rate	(mg/d)	5.12E+08
	Q^2	CSTR Influent Flow	(L/d)	46329
	X_a^2	CSTR Influent Active Biomass	(mg/L)	11062
	$m_a^{2\text{-CHECK}}$	CHECK CSTR Influent Active Mass Rate	(mg/d)	5.12E+08
3	m_a^3	CSTR Effluent Active Mass Rate	(mg/d)	5.64E+08
	Q^3	CSTR Effluent Flow	(L/d)	46329
	X_a^3	CSTR Effluent Active Biomass	(mg/L)	12178
	$m_a^{3\text{-CHECK}}$	CHECK CSTR Effluent Active Mass Rate	(mg/d)	5.64E+08
4	m_a^4	Effluent WW Active Mass Rate	(mg/d)	1.69E+07
	Q^4	Effluent WW Flow	(L/d)	29700
	X_a^4	Effluent WW Active Biomass	(mg/L)	570
	$m_a^{4\text{-CHECK}}$	CHECK Effluent WW Active Mass Rate	(mg/d)	1.69E+07
5	m_a^5	Settled Active Mass Rate	(mg/d)	5.47E+08
	Q^5	Settled Flow	(L/d)	16629
	X_a^5	Settled Active Biomass	(mg/L)	32910
	$m_a^{5\text{-CHECK}}$	CHECK Settled Active Mass Rate	(mg/d)	5.47E+08
7	m_a^7	Return Active Mass Rate	(mg/d)	5.12E+08
	Q^7	Return Flow	(L/d)	15572
	X_a^7	Return Active Biomass	(mg/L)	32910
	$m_a^{7\text{-CHECK}}$	CHECK Return Active Mass Rate	(mg/d)	5.12E+08
6	m_a^6	Waste Active Mass Rate	(mg/d)	3.48E+07
	Q^6	Waste Flow	(L/d)	1056
	X_a^6	Waste Active Biomass	(mg/L)	32910
	$m_a^{6\text{-CHECK}}$	CHECK Waste Active Mass Rate	(mg/d)	3.48E+07