A Cost Analysis of Two-Stage Thermophilic-Mesophilic Anaerobic Wastewater Treatment Systems

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ABSTRACT

Anaerobic bacteria have displayed great potential as a wastewater treatment method because of their efficiency, high methane yield, and low input requirements. In the past, studies have investigated various aspects of these systems, including their chemical oxygen demand (COD) removal efficiency, methane yield, and retention times. However, they have mostly focused on single stage high rate anaerobic (HRAA) reactors such as the upflow anaerobic sludge blanket (UASB) reactor. In this paper, we aim to synthesize the results of these studies to investigate the advantages of building upon the UASB via a two-stage thermophilic-mesophilic (T-M) reactor system with an anaerobic filter (AF) as the acidification tank. The key constraint for adopting two-stage anaerobic systems is primarily related to construction and O&M costs. Therefore, we propose adjusting pH levels and influent flow rates to enhance energy generation and cost-efficiency. This approach aims to encourage greater utilization of two-stage anaerobic systems for wastewater treatment by lowering costs and increasing profits.

Introduction

Anaerobic digestion (AD) is one of the most efficient methods to clean wastewater while producing methane, simultaneously tackling air and water pollution. AD implementation in wastewater treatment plants (WWTPs) produces biogas with 50-75% methane content (Author, 2012), which can be used as energy with a total content of 39.8 MJ/m^3 (Author, 2021).

In AD, the use of anaerobic microorganisms for treatment provides various benefits over aerobic digestion. Because oxygen is not a necessary component, anaerobic reactors can be smaller, requiring less energy input for mixing, and costing less for construction. AD also allows effluent wastewater to carry important nutrients like nitrogen and phosphorus, potentially minimizing the necessity for fertilizer by providing effluent that can serve as an alternative source of nutrients.

Literature on AD primarily focuses on single reactors and their individual potential for biogas yield, retention time, and COD removal efficiency. Moreover, very few studies investigate the cost of two-stage systems despite it typically being the primary hindrance to their construction in developing countries where they are necessary. Therefore, this paper aims to analyze the cost benefits of two-stage T-M reactor systems and the conditions required to maximize profit.

High Rate Anaerobic Reactors (HRAAs)

HRAAs are any reactor design which utilizes anaerobic microorganisms to break down organic materials in wastewater. The usage of active sludge in HRAAs provides many benefits over other wastewater treatment methods.

It lowers hydraulic retention times (HRT) due to high biomass concentrations and reduces COD by 80-90% due to a high concentration of active sludge (Author, 2010).

HRAAs are mainly characterized by immobilizing biomass, so different designs of HRAAs are differentiated by their method of doing so. Author (2003) reported that the two main determinants of success for a wastewater treatment system are good contact between the incoming substrate and sludge mass in the system, as well as retention of a large sludge mass in the system. Consistent contact between the influent and sludge of the system maximizes the efficiency of the wastewater treatment and reduces retention times. The maintenance of a large sludge mass is also vital, as loss of sludge will hinder the system's performance and can also generate large costs; therefore, a successful treatment system should be able to maintain or quickly replenish any sludge mass in the system.

Anaerobic Filter (AF) Reactor

As seen in Figure 1, an AF primarily consists of one or more vertical filter beds with inert media to support biomass and an entrapment mechanism for unattached flocs. Influent is pumped up through the filling material to achieve contact between the microorganisms and wastewater. A filter blanket supports any biomass separated from the effluent, and the filters may be operated with ascending or descending flow. An ascending flow produces high concentrations of suspended biomass and forms biofilm in the structure of the fixed bed. Thus, the AF fulfills the first condition for a successful wastewater treatment system by keeping biomass in suspension and assuring contact between microorganisms and the influent material (Author, 2014). On the other hand, a descending flow is used for effluent with a high concentration of inorganic sulfur.

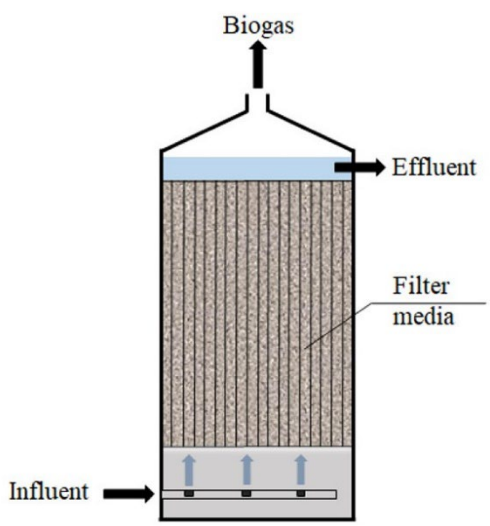

Figure 1. Schematic diagram of an anaerobic filter reactor (Author, 2018).

Common support media include synthetic plastic or ceramic tiles with a high volume and specific surface area. Because the unique media retain biomass well, the AF can achieve long solid retention times (SRT) of up to 100 days even with an HRT of 0.5-4 days and an organic loading rate (OLR) of 5-15 kg COD/m^3/d (Author, 2008).

Because of the inclusion of filter media in its design, the AF has low HRT and high substrate removal efficiency, allowing it to perform hydrolysis well. In addition, the effluent has low suspended-solids (SS) concentration, eliminating the need for solid separation and recycling required for some HRAAs. In addition, the AF's relatively simple design leads to generally lower construction and O&M costs (Author, 2018).

Upflow Anaerobic Sludge Blanket (UASB) Reactor

The UASB is widely recognized as the most efficient and widely applicable reactor and is mainly used in situations requiring the recovery of water after treatment (Author, 2014).

In the UASB (Figure 2), a wastewater and sludge mixture is fed through the internal influent system, then rises and passes through the three-phase separator at the top. The UASB also has a biological reaction zone where the influent passes through the active sludge, converting organic compounds into methane and carbon dioxide (Author, 2010).

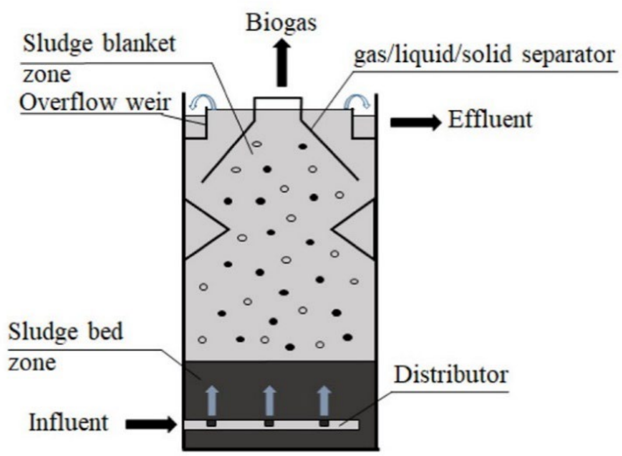

Figure 2. Schematic diagram of an upflow anaerobic sludge blanket reactor (Author, 2018).

The design of the UASB allows it to fulfill both conditions for treatment systems. The influent is distributed uniformly over the bottom of the reactor and then rises through the sludge; thus, contact between the influent and active sludge is guaranteed. Additionally, the phase separator retains dispersed solids and returns them to the digester compartment, thus maintaining a large sludge mass.

Thermophilic and Mesophilic Reactors

Thermophilic reactors have temperatures of greater than 45°C, and mesophilic reactors have temperatures of 25-45°C. These different temperatures promote the growth of specific microorganism species, allowing for further optimization of AD systems.

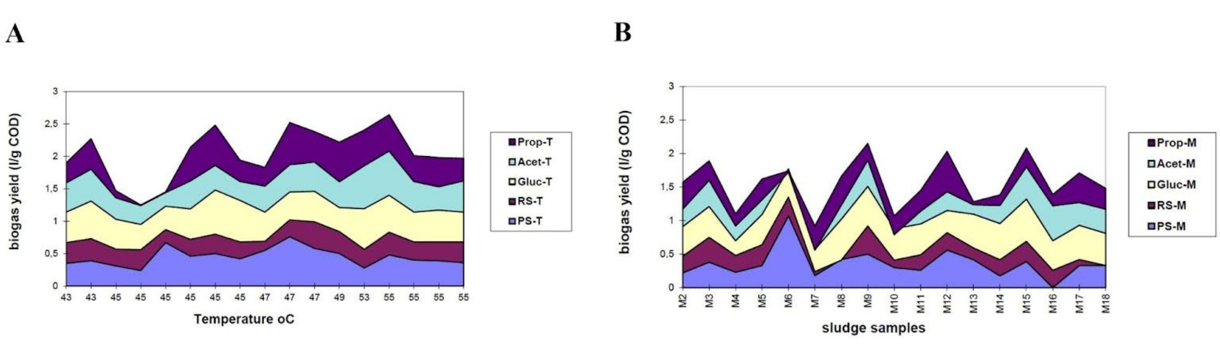

Figure 3. Biogas yields of each type of reactor. Figure 3A shows the yield of thermophilic sludge at varying temperatures, and Figure 3B shows the yield of mesophilic sludge with varying substrates (Author, 2000).

Thermophilic AD in particular has been shown to tolerate higher OLR and degrade organic matter more efficiently (Author, 2015, Author, 2000). Both thermophilic and mesophilic reactors demonstrate high biogas yield, as seen in Figures 3A and 3B. The activity of thermophilic sludge decreased slightly after the initial temperature change, but after balancing of the conditions, the biogas yield of the thermophilic reactor was always higher than the mesophilic reactor (Author, 2000).

AF/UASB T-M Two-Stage Reactor and Operating Conditions

The first reactor in a T-M system which performs most of the hydrolysis, or the AF in our system, can also be called the acidification tank (AT). The second reactor, or the UASB, can be called the methanogenic reactor (MR).

The AF/UASB System

Despite the UASB's efficiency in biogas production and efficiency, the rate-limiting step of the UASB AD is its poor hydrolysis, leading to a higher HRT in order to fully process organic materials in influent. Author (2010) found the reason to be the settling, adsorption, and entrapment of particulate organics in influent, making the hydrolysis of these particles a significant part of the UASB's retention time. Thus, preceding it with an AF utilizes the AF's high substrate removal efficiency to break down organic materials in the influent, thereby allowing the UASB to perform AD more efficiently.

The AF/UASB system, while performing well in various operating conditions and with different loading substrates, is best suited for domestic sewage in tropical countries (Author, 1998). The system can handle different situations, even unfavorable conditions where the UASB effluent has very low COD, biological oxygen demand (BOD), and SS concentrations.

Thermophilic-Mesophilic (T-M) System

Biogas Yield

Because of the ideal conditions caused by the different temperature in each reactor, the T-M system in Figure 4 has a 42.4% higher methane yield than any HRAA reactor (Author, 2021).

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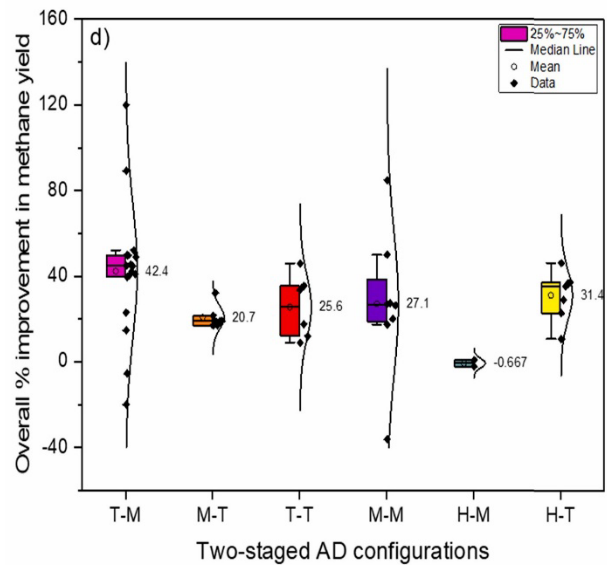

Figure 4. Increase in methane yield from two-stage AD compared to a control group of single-stage AD, excluding outliers (Author, 2021).

A breakdown of the methane production of a two-stage T-M system after the thermophilic acidogenic reactor and then the mesophilic methanogenic reactor can be seen in Author (2017). As expected, methane production after the thermophilic reactor was low because of a focus on hydrolysis and breaking down organic material, but the mesophilic reactor had high methane production (see Figure 5).

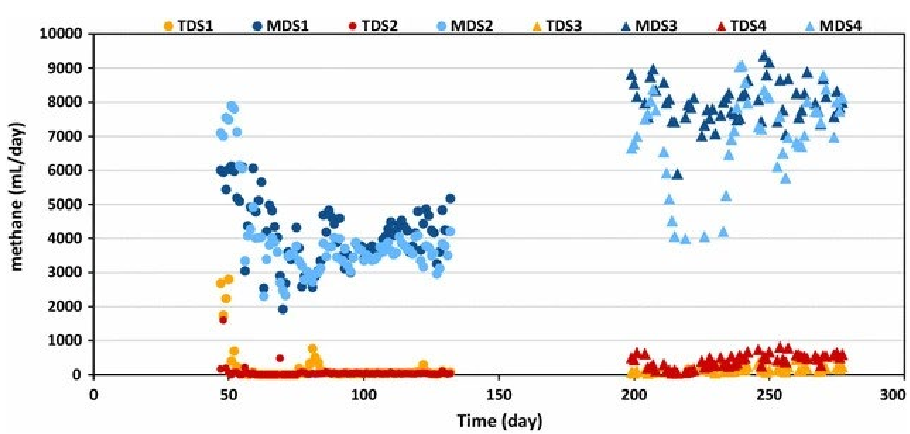

Figure 5. Daily methane production by 8 digesters over time with different HRT and operating temperatures (Author, 2017).

Empirical data of increased methane production from T-M systems compared to single-stage systems can be seen in data from the operation of Köln-Stammheim (Figure 6). The two-stage system reduced the organic solid (oTS) concentration by 60% compared to a reduction of 48% by the single-stage reactor, and had 16.5% higher specific gas production (Author, 1997).

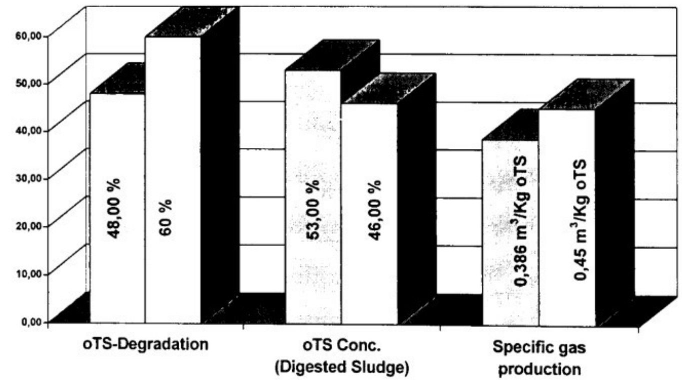

Figure 6. Comparison of oTS reduction, concentration, and specific gas production of a single-stage mesophilic reactor (left) with a two-stage T-M system (right) (Author, 1997).

Energy Production

As two-stage AD systems, especially T-M systems, require energy input in the form of mixing energy requirements and temperatures, an estimate of the net energy yield of the system can be used to indicate the energy balance of the system. Furthermore, energy production is an important component in cost analysis, as the main source of profit from AD systems is their biogas production.

Energy Equation

The total energy produced by an anaerobic digester as electrical and thermal energy can be modeled by **Equation 1**, modified from Author (2007).

Equation 1: Total energy production of the system:

$$P_{ET} = V_{CH_4} H_C (\varepsilon_E + \varepsilon_T)$$

where P_{ET} represents the total electrical and thermal energy from the digester, V_{CH_4} represents its daily methane production in m^3/d, H_C represents the calorific value of methane in kWh/m^3, and ε_E and ε_T represent the electrical and thermal degree efficiency of methane, 35% and 50% respectively. Given the operating conditions and data from an anaerobic system, this equation can be used to estimate its total energy production and thus infer its revenue and profit (Author, 2007).

Methane Yield, Production Rate, and Net Energy Yield

With an initial volatile solid (VS) loading rate of 9 g-VS L^{-1}, the system had a methane yield of 315 mL CH_4 g^{-1} VS, methane production of 52.8 m^3 CH_4 ton^{-1} MSW, and a methane production rate of 27.73 mL CH_4 g^{-1} VS d^{-1} (Author, 2020). Past literature has reported various data for the increase of methane production of two-stage T-M compared to single-stage AD ranging from a 7-15.8% increase (Author, 2013) to a 20-40% increase (Author, 2013) based on reactor size, loading rate, and operating conditions.

Author (2021) found the net energy yield of a T-M system to be 217,927 kWh/d: 231,801 kWh/d are produced by the phase digesters, and 13,873.8 kWh/d are consumed as energy input. With an output 1,570.78% greater than the input, the system proves itself to be extremely efficient at generating electricity.

Cost Optimization and Analysis

Profit

The annual profit of a T-M system is $5.11M per year, with $6.16M in revenue and $1.05M in costs (Author, 2021). Compared to a mesophilic-thermophilic system that only generates $1.61M of profit, the T-M system makes over 200% more thanks to a higher biogas production.

Operation Cost Components

Author (1991) separated the operation costs of an anaerobic system into four main aspects. First, the effluent disposal cost is based on the organic carbon content (BOD and COD), SS concentration, grease, pH, and volumetric flow rate of the effluent. This is mainly composed of the cost of discharging organics, calculated based on the glucose and organic acids within the system's effluent.

The second cost component is based on the chemical agents needed to maintain the pH levels of each reactor at ideal conditions. Nutrients are used to provide trace elements deficient in the substrate, but only make up a small portion of the cost because of the small quantity required for anaerobic bacteria. This also includes conditioning agents like caustic soda used to maintain AT pH.

Next, the negative cost, or benefit, of biogas production in the AT can be modeled by Equation 1, and the benefit for the MR can be modeled by Equation 2 (Author, 1991).

Equation 2: Benefit of the acidification tank:

$$0.15 \cdot \frac{1}{3600} \cdot 0.35 \cdot 802 \cdot \frac{1}{24.5} \cdot q_{v1 \cdot CH_4}$$

Equation 3: Benefit of the methanogenic reactor:

$$0.15 \cdot \frac{1}{3600} \cdot 0.35 \cdot 802 \cdot \frac{1}{24.5} \cdot q_{v2 \cdot CH_4} \text{ with } -ve \text{ if } p_{CH_4} > 0.6;\ +ve \text{ if } p_{CH_4} < 0.6$$

Equations 2 and 3 are based on the calculations for biogas cost terms using the following data: an assumption of 35% efficiency for the conversion of biogas into usable electricity; the cost (profit) of electricity as $0.15/kWh; and the energy gained from the combustion of methane as 802 kJ/mol of methane. Important also to note is the use of only some methane generated in the MR. Usable biogas must have at least 60% methane content, so the biogas generated in the AT usually has insufficient methane content and is discarded. In Equation 3, the cost for the MR demonstrates a negative value (profit) for biogas with methane content (p_{CH_4}) greater than 60%, and a positive value for biogas with less than 60% methane content.

Finally, the last cost component is the cost of failure, or the cost of losing biomass from the MR. As the retention of biomass within the reactor is essential to the system, the loss of biomass from the reactor limits the biogas production rate and thus lowers the revenue of the system. The cost can also be represented as the cost of re-establishing the bacteria levels of the reactor to a sufficient concentration.

Capital and O&M Equations

The capital costs of the reactor system including the construction and facility costs can be calculated by Equation 4 found by Author (2007), where y represents the capital cost, and x is the treatment volume in m^3/d.

Equation 4: Reactor system capital costs:

$$y = 494x^{-0.20}$$

Author (2007) also calculated Equation 5 for the operation and maintenance (O&M) costs, where y represents the O&M costs, and x is the treatment volume in m^3/d.

Equation 5: O&M costs:

$$y = 457x^{-0.49}$$

Thus, combining the capital and O&M costs yields a total cost estimate of 6.16-9.67 US$/m^3/d (Author, 2007). Of this cost, the main component is capital cost, which makes up 46-57% of the total cost. Thus, the two-stage system is expensive mostly because of high construction costs, and not because of the expense of maintenance.

Cost Optimization

The most important cost term in the two-stage reactor system is the production of methane for profit. Therefore, optimal operation of the AT should change pH and flow rate based on the increase or decrease of methane content and biogas production.

pH Minimization

One method of minimizing cost is achieving the minimum pH without causing process failure. The reactor must remain within a certain pH range for good fluidization of the biomass depending on the microorganism, but even small reductions in the AT pH can reduce cost from the consumption of caustic soda. Author (1991) found the cost optimum pH to be 5.75 for the AT reactor in the two-stage system because of the requirement for biogas to be at least 60% methane content to be useful (Figure 7).

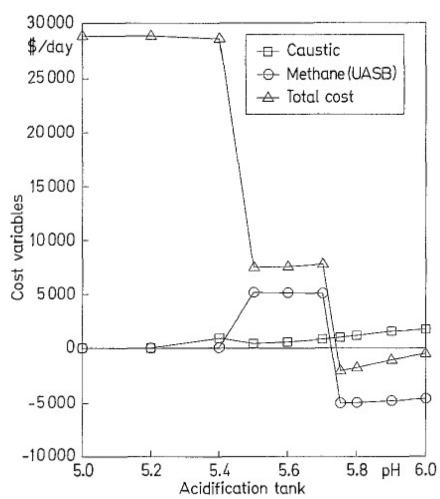

Figure 7. Operating costs for an acidification tank with changing pH and a fixed flow rate of 72.7 m^3/h (Author, 1991).

Substrate Loading Rate Maximization

Increases in the recycle flow rate increase the profit of the system because of a reduction in the alkalinity required to maintain the proper pH for the AT; the caustic consumption rate and effluent COD decrease while the methane generation of both the AT and MR increase. However, the decrease in caustic consumption rate should be monitored, as a decrease in caustic consumption can lead to a fall in the MR pH and inhibit the activity of the methanogenic bacteria.

Author (1991) reported in Figure 8 that the lowest operating cost is at a recycle flow rate of 324.5 m^3/hr. After this point, the methane content of the produced biogas falls below the 60% threshold, and the cost term becomes positive. However, this flow rate falls outside the normal range of recycle flow rates (50-100 m^3/hr), so the system should simply be operated at the maximum possible recycle flow rate.

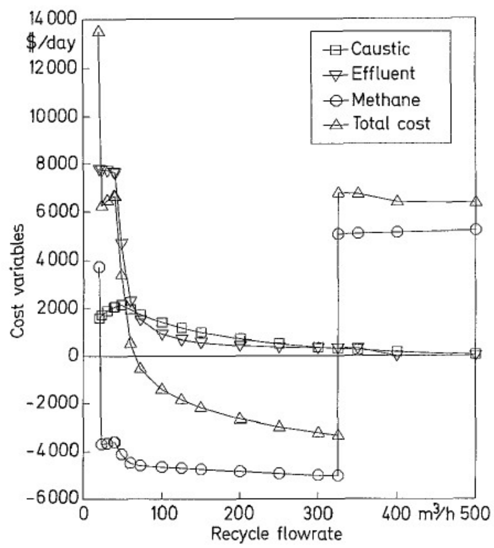

Figure 8. Operating costs for a system with a constant AT pH of 6 and a changing recycle flow rate (Author, 1991).

Discussion

Two-stage thermophilic-mesophilic systems have proven to be extremely cost-efficient methods of processing wastewater when variables such as temperature and pH are optimized. The individual roles of the acidogenic AF reactor and methanogenic UASB reactor in the two-stage process ensure thorough COD removal and hydrolysis, and together they produce high quality effluent and biogas. The efficacy of thermophilic and mesophilic conditions in decomposing organic waste further enhances the system by creating an optimal environment for bacteria in each reactor.

A cost analysis on the system reveals that its main expense is a fixed cost spent on construction, and the primary revenue stream comes from methane production. By optimizing the system for methane production, the earnings quickly exceed the loss, thereby providing a viable system for developing countries to tackle wastewater management, energy generation, and income generation simultaneously.

Conclusion

Compared to traditional methods of wastewater treatment and other anaerobic systems, the two-stage AF/UASB thermophilic-mesophilic system has greater biogas yield, and many methods are beneficial for its cost reduction. By analyzing past literature about two-stage anaerobic systems and individual reactors, the research analyzes the benefits of each individual reactor and the proposed system as a whole, and thus develops a potential reactor combination to efficiently implement anaerobic wastewater treatment. In addition, by quantifying the biogas production of the system, identifying major cost components, and providing operating conditions for cost optimization, the research explains the historically high costs of two-stage anaerobic systems as a whole, as well as ways to minimize it.

The conclusions drawn from our research highlight an important step in widespread implementation of the most efficient anaerobic systems. Since construction and usage of two-stage systems in particular are often limited by cost in underdeveloped regions, being able to minimize expenses and find sustainable solutions for high quantities of wastewater is important for feasible biogas production. As a result, future research should focus on real-world applications of small-scale two-stage AF/UASB thermophilic-mesophilic systems in testing environments to extract empirical data and test physical limitations on the cost parameters of pH and flow rate that we identified. In addition, research should look into methods of optimizing the amount of usable biogas with at least 60% methane content from the MR to maximize the energy produced by the system.

Limitations

Because of the resources necessary to construct an anaerobic system, we were unable to collect data from a small-scale model of our proposed system. We were also unable to build a simulation of the system. As a result, our analysis is limited to past data of two-stage systems, AF/UASB systems, and thermophilic-mesophilic systems. Furthermore, there is an overall lack of empirical data of actual implementation of this system, so we relied mostly on small-scale experiments done in a lab setting.

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