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Performance Evaluation of H-UASB Reactors with Ceramic Membrane Filtration for Paper and Pulp Industry Wastewater Treatment and Energy Recovery

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Abstract: The paper and pulp industry generates high-strength wastewater containing elevated COD, suspended solids, and recalcitrant organics, necessitating advanced treatment solutions that couple efficiency with resource recovery. This study evaluates the performance of a hybrid treatment system integrating a Hybrid Upflow Anaerobic Sludge Blanket (H-UASB) reactor with ceramic membrane filtration. Reactor performance was assessed in terms of pollutant removal, biogas generation, and effluent polishing efficiency. Day-wise monitoring revealed dynamic influent and effluent variations, with COD and TSS reductions demonstrating effective, though fluctuating, treatment performance. Biogas production ranged from 1.8 to 4.4 L/day, confirming the reactor's potential for energy recovery under variable loading conditions. The ceramic membrane unit achieved COD removal efficiencies between 42.4% and 56.5%, though progressive efficiency declines highlighted membrane fouling as a key operational constraint. Effluent quality remained within acceptable limits during initial operation but showed deterioration with continued fouling, underscoring the need for optimized cleaning intervals and fouling mitigation strategies. Overall, the results establish the integrated H-UASB–ceramic membrane system as a promising approach for sustainable treatment of paper and pulp industry wastewater, combining pollutant reduction with renewable energy generation. However, long-term stability and large-scale deployment depend on fine-tuning operational parameters and managing fouling dynamics

Key Words: Paper and pulp wastewater; H-UASB reactor; Ceramic membrane filtration; Biogas production; Energy recovery; Membrane fouling

1. Introduction

The paper and pulp industry are a major consumer of freshwater and a significant generator of high-strength industrial effluents. These wastewaters typically exhibit elevated levels of chemical oxygen demand (COD), total suspended solids (TSS), recalcitrant organic matter, and chromophoric compounds, posing serious environmental challenges when insufficiently treated. Conventional treatment systems, although capable of reducing pollutant loads, are often constrained by high energy requirements, limited operational stability, and a lack of resource recovery pathways. These limitations have driven increasing interest in hybrid systems that integrate biological treatment, physical separation, and energy recovery.

Hybrid upflow anaerobic sludge blanket (H-UASB) reactors represent a promising biological treatment option for such effluents. They combine effective degradation of organic matter with simultaneous biogas generation, contributing both to pollutant reduction and renewable energy recovery. Nevertheless, residual solids, colour, and microbial contaminants in the effluent frequently necessitate additional polishing to achieve discharge standards.

Ceramic membrane filtration has emerged as a suitable post-treatment strategy, offering robustness, chemical resistance, and high efficiency in removing suspended and dissolved contaminants. However, membrane fouling and the need for periodic cleaning remain critical barriers to long-term application.

This study evaluates the integrated performance of an H-UASB reactor coupled with ceramic membrane filtration for treating paper and pulp industry wastewater. The assessment focuses on three dimensions: (i) treatment efficiency through influent–effluent performance metrics, (ii) biogas yield as an indicator of energy recovery, and (iii) filtration efficiency, effluent quality, and fouling dynamics. The findings aim to advance understanding of hybrid treatment systems, with a view to optimizing both operational performance and sustainability.

2. Literature Survey

The paper and pulp industry generates large volumes of wastewater that is both complex and high in organic load. These effluents typically contain elevated concentrations of chemical oxygen demand (COD), total suspended solids (TSS), lignin-derived compounds, and colour-causing organics, which collectively hinder biological degradation and pose persistent challenges to conventional treatment systems. The variability of wastewater characteristics across mills further complicates treatment, necessitating robust and adaptable solutions capable of achieving high pollutant removal while enabling opportunities for resource recovery. Anaerobic high-rate technologies, particularly upflow anaerobic sludge blanket (UASB) and hybrid UASB (H-UASB) reactors, have been widely reported as effective first-stage treatments for pulp and paper mill effluents. These systems can achieve substantial COD removals at low hydraulic retention times (HRTs) and are attractive due to their relatively low energy demand compared with aerobic processes. In addition, they facilitate biogas generation, providing an energy-rich by-product that contributes to improved process economics. However, performance outcomes vary considerably depending on influent characteristics, organic loading rates (OLRs), and operational stability. Literature emphasizes that under optimized conditions, biogas production can significantly offset energy requirements of mill operations, aligning wastewater treatment with circular economy objectives. Despite these advantages, the effluent from UASB and H-UASB reactors often requires post-treatment due to incomplete removal of suspended solids, residual COD, and colour. In this context, ceramic membrane filtration has emerged as a promising polishing step. Ceramic membranes, compared with polymeric alternatives, offer superior thermal and chemical resistance, longer operational lifespan, and consistent separation efficiency for particulates and recalcitrant organics. Studies demonstrate that when integrated downstream of anaerobic treatment, ceramic membranes produce stable effluent quality that can comply with regulatory discharge standards. Nevertheless, membrane fouling remains the principal operational limitation, driven by mechanisms such as cake deposition, pore blockage, and the accumulation of soluble microbial products. Fouling not only reduces system efficiency but also increases operational costs due to frequent cleaning requirements. Consequently, long-term performance and economic feasibility depend heavily on flux optimization, pre-treatment strategies, and effective cleaning protocols. Hybrid systems that integrate UASB/H-UASB reactors with ceramic membrane filtration are increasingly highlighted as effective solutions for pulp and paper wastewater treatment. Such configurations demonstrate synergistic benefits, with anaerobic reactors reducing bulk organic load and generating energy, while membranes ensure high-quality effluents. However, most published studies to date are limited to laboratory or pilot-scale trials, often under controlled or short-term conditions. Critical knowledge gaps remain in areas such as long-term fouling behaviour under variable industrial conditions, techno-economic assessments of large-scale deployment, and system optimization for energy recovery. Addressing these gaps is essential to translating promising laboratory outcomes into robust, industrially viable treatment strategies.

3. Methodology

3.1 Ceramic Membrane Filtration

Ceramic membrane filtration is very vital for the improvement of the performance of a (HUASB) reactor since it helps in the separation of the treated effluent from the residual sludge. The process of filtration that incorporates the ceramics membranes aims at improving the efficiency of the treatment as well as obtaining the best quality of the effluent. The Ceramic Membrane Filtration is shown in Figure 1.

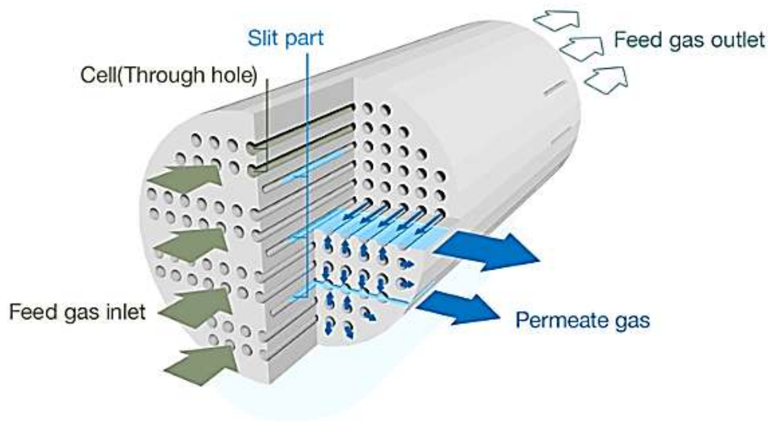

Figure 1: Ceramic Membrane Filtration

3.1.1. Effluent Separation

Effluent water being treated in the H-UASB reactor moves up through the layers and encounters the ceramic membrane that is fixed at the top part of the reactor. This is a physical barrier that is composed of ceramic and keeps treated water in the same reactor while the remaining sludge is left. The membrane pore size is usually in the micro to ultrafiltration, thus, while permeating clean water, it rejects suspended solids, microorganisms, and residual fuzzy sludge. The phenomenon guarantees that only clean water only leaves the reactor, while sludge containing dissolved organics, and microbial mass is retained in the reactor. The proposed HUASB reactor Ceramic Membrane is shown in Figure 2.

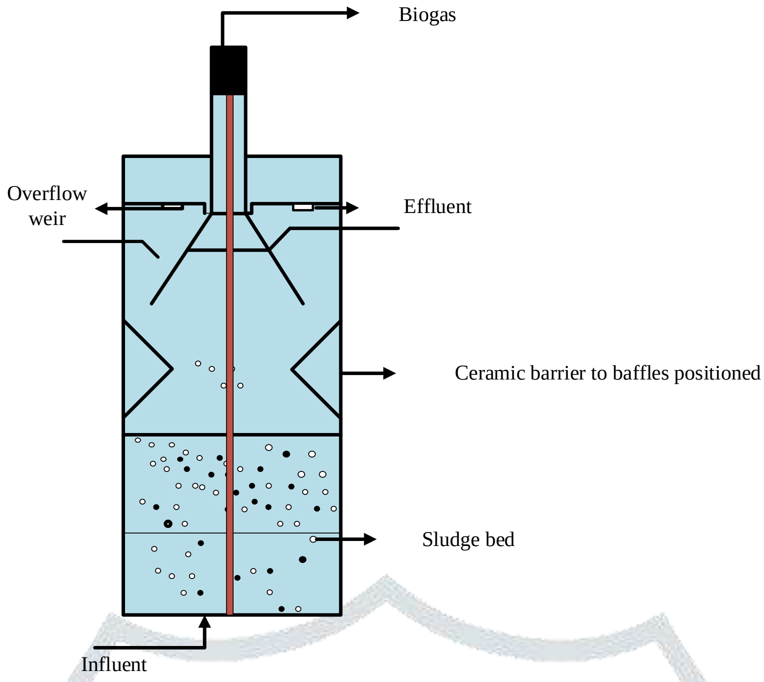

Figure 2: Hybrid UASB reactor (proposed) ceramic membrane

The ceramic membrane has fine pores that let it to filter small particle and microorganism without effortless. This aids in producing good quality effluent that will have to meet various discharge rates that are integral in environmental conservation. The membrane also helps to control and eliminate suspended solid and microorganisms from the water flow hence enhancing the quality of the effluent. The use of ceramic membrane, especially when it is placed at the top of the reactor also allow for proper flow of the treated water. During the upward flow of the wastewater and upon its arrival at the membrane, the water is channelled through the filtration process which sees to it that the water and the sludge are well separated.

3.1.2. Membrane Cleaning

Ceramic membranes are well-known for their high-end durability and poor fouling characteristics, but they need some level of cleaning and replacement to enhance their efficiency. Ceramic membranes are used with lesser fouling issues compared to polymeric membranes. Fouling is the deposition of particles or biomass on the surface of the membrane they decrease the filter effectiveness. Certain inherent characteristics of the porcelain material, including thermal and chemical stability, define the material's fouling and chemical deterioration levels. However, independently on the fouling despise that ceramic membranes have, some sludge or particles may deposit on their surface after prolonged use. These deposits must be cleaned periodical to make the membrane works effectively. The cleaning can be conducted manually, by backwashing, use of chemicals or through physically applying force to the fouled surfaces. The two most common processes that are involved in the cleaning to the sand are backwashing and rinsing. Backwashing involves a reversal of water flow to start removing particles that may have accumulated. Chemical cleaning involves the use of chemicals to dissolve or if perchance to remove the fouling agents. Cleaning can also be carried out by washing or rubbing the membrane surface in a physical method. Period for cleaning of membrane depends on the characteristic of the treated wastewater, conditions under which the membrane operates, and magnitude of foulant layer. There is scheduling for monitoring and maintenance with the purpose of effective cleaning that is done at right frequency so that fouling does not build up and filtration becomes less efficient. It should be noted that strategies of fouling control involving cleaning solutions and cleaning techniques depend on the type of fouling. For instance, the acid solutions are employed as cleaning fluids to dissolve inorganic scales whereas, alkaline solutions for clearing of the organic foulants. The cleaning process needs to be highly controlled not to cause any harm to the ceramic membrane but at the same time remove fouling materials. The Membrane before and after cleaning is shown in Figure 3.

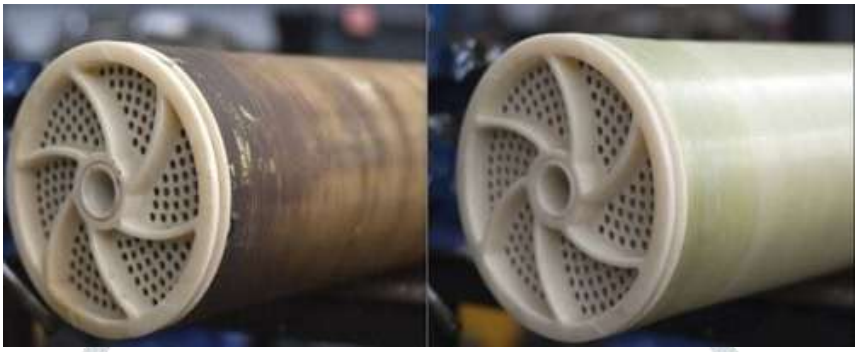

Figure 3. Membrane before and after cleaning

4. Result and Discussion

An electrochemical treatment process's efficiency is examined concerning several operational parameters. After the impact of current density was investigated, it was shown that although larger current densities generally improve removal efficiency, they can also result in higher energy and operating expense requirements. The treatment result was shown to be highly influenced by the starting pH of the solution, with the best pH levels promoting higher degradation of pollutants. Because higher COD levels required more intensive treatment, the water's COD content, which also affected the effectiveness of the treatment, indicated how much organic matter was present. Through testing various electrode designs, it was shown that specific materials and materials' electrochemical characteristics might lead to improved performance. Finally, a variation in the distance between the inner electrodes demonstrated how a reduction in distance might result in a more effective removal of contaminants from the reactor by improving current distribution and lowering resistance. To accomplish successful and affordable electrochemical water treatment, our results emphasize how crucial it is to optimize these parameters.

4.1 Reactor Performance Metrics

4.1.1 Overall Treatment output

Treatment output is the total volume of wastewaters treated and an indication of an overall assessment of the efficiency / effectiveness of the wastewater treatment system. Day wise findings depict the system performance as slowly characteristic, thus providing an unseen variance in the treatment effectiveness. Some observations considered include the trends in the COD removal efficiency, which shows how the system achieves the conversion of the influent's organic pollutants. The analysis of effluent quality regarding COD and TSS relates to the effectiveness of the treatment process having a relatively good conformity to the quality standards with some fluctuations indicating the necessity to optimize the operational parameters. The fluctuation of other factors including HRT as well as power usage only serve to highlight the necessity of maintaining the right conditions for operation to strike the ideal balance between effective treatment and power utilization. It also indicates that membrane fouling or changes in system parameters may affect performance, which in essence asserts that regular operation testing and some sort of maintenance to keep the system in optimum condition is critical.

The data collected over the first four days illustrates the reactor performance parameters and the H-UASB reactor's operational effectiveness. Day 1 showed an intake value of 219.05. The outlet value was 470.3. When compared to the treated effluent, this suggests that the influent has a comparatively higher concentration of pollutants. Day 2 showed a slight decrease in the inlet concentration to 213.05. However, the outflow concentration increased to 489.442 by then. This shift implies that, even as the reactor processed the wastewater, there still has been a slight increase in the treated effluent concentration, due to changes in influent quality or operational situations. Day 3 showed an increase in the total concentration of pollutants as both the exit and inlet concentrations increased to 519.1 and 252.46, respectively. On Day 4, the intake concentration rose to 277.63 while the outflow concentration marginally dropped to 499.83. The dynamic aspect of the reactor's performance is emphasized by the patterns of varying outlet and inlet concentrations, which reflect changes in influent quality, treatment efficiency, and operational stability. These measurements are essential for determining the way the reactor performs in lowering pollutant levels and streamlining the entire treatment procedure.

4.1.2 Biogas Production Rates

Wastewater treatment efficiency is best explained by the analysis of biogas production rates in the process. The production rates relate to the efficiency of the system in the conversion of organic matter into biogas, which is one of the variables of the anaerobic digestion efficiency. Fluctuations in the biogas production are depending on organic loading rates, the type and strength of the substrate as well as the efficiency of the biological process and process conditions like hydraulic retention time and the temperature of the system. There is a direct correlation between higher biogas production rates and more efficient breakdown of organic matter to support better treatment results. However, performance measurement and optimization are critical in keeping the biogas production stable and running within the indicated design parameters. Biogas management also includes the optimization of the treatment process while at the same time ensuring the most effective retrieval of energy resources.

The biogas production rates from the H-UASB reactor ranged between 1.8 and 4.4 liters per day. This variation reflects the dynamic nature of the anaerobic digestion process, influenced by factors such as the composition of the influent wastewater, reactor operational conditions, and microbial activity levels. The lower end of the range, 1.8 liters per day, indicates periods of lower biogas generation, possibly due to fluctuations in influent quality or reactor stability. Conversely, the higher end of the range, 4.4 liters per day, represents more optimal conditions for biogas production, where the reactor efficiently decomposes organic matter and generates higher volumes of methane and carbon dioxide. These production rates are critical for evaluating the reactor's overall efficiency and effectiveness in converting organic waste into valuable biogas.

4.1.3 Ceramic Membrane Filtration Performance

The results expressed by the ceramic membrane filtration system show a complex effectiveness for treating wastewater. Based on the variation of filtration efficiency over the observed period, it could be ascertained that the system helps in decreasing the contaminants. Such efficiency explains the membrane's ability to eliminate organic matter and suspended solids in the influent leading to improved quality of the effluent with the increasing efficiency. The treated water quality also varies depending on the seasons; however, the efficiency of the treatment system increases with time showing that the system learns the operational conditions. However, differences in the result imply that parameters like membrane fouling and working alteration affect the performance of the methodology. Fouling remains a significant problem when employing membranes and is manageable through proper management and proper inspection and care of the membranes. In summary, the effectiveness of the system proves that while designing the filtration system, there are pertinent factors that should be taken into consideration equally to ensure high quality and constant effluent.

4.1.3.1 Filtration Efficiency

Filtration efficiency is typically calculated as the percentage of the influent that is successfully filtered out or removed by the membrane. It can be determined using Equation: 4.1.

$$\text{Filtration Efficiency} = (1 - \frac{\text{Concentration of Parameter in Effluent}}{\text{Concentration of Parameter in Influent}} \text{x } 100\%) \qquad (4.1)$$

For COD removal, the calculation of the efficiency for each day is shown in Figure 4.

Day 1: (1−0.466) ×100% = 53.4%

Day 2: (1−0.435) ×100% = 56.5%

Day 3: (1−0.486) ×100% = 51.4%

Day 4: (1−0.556) ×100% = 44.4%

Day 5: (1−0.576) ×100%=42.4%

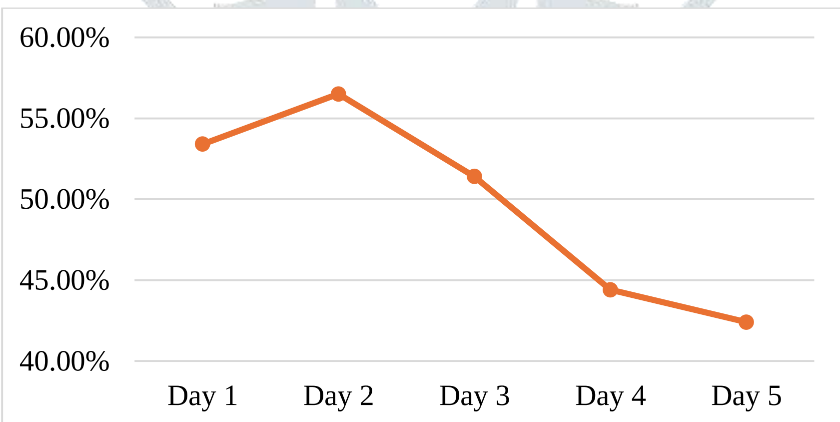

Figure 4: Regular filtering efficiency

4.1.3.2 Quality of Treated Effluent

The quality of treated effluent can be assessed based on parameters such as COD and Total Suspended Solids (TSS) are as follows.

Day 1: Effluent COD = 219.05 ppm, TSS = 90 mg/L

Day 2: Effluent COD = 213.05 ppm, TSS = 92 mg/L

Day 3: Effluent COD = 252.46 ppm, TSS = 92 mg/L

Day 4: Effluent COD = 277.63 ppm, TSS = 93 mg/L

Day 5: Effluent COD = 288.0 ppm, TSS = 93 mg/L

These values provide insights into how effectively the membrane filtration process is removing contaminants. Higher COD and TSS values indicate potential issues with filtration efficiency or membrane performance.

4.1.3.3 Membrane Fouling and Cleaning Intervals

Membrane fouling is a common issue in filtration systems and affects performance over time. Cleaning intervals are determined based on the rate of fouling, which can be inferred from changes in filtration efficiency and increased pressure drops. Typically, fouling is observed as a decline in filtration efficiency and an increase in operational pressure. Based on the provided data, if the COD removal efficiency decreases significantly over days, it suggests membrane fouling. For cleaning intervals:

- Initial Fouling Observation: If the COD removal efficiency drops from 53.4% on Day 1 to 42.4% on Day 5, it indicates that fouling is occurring.
- Cleaning Interval: In practice, membranes might be cleaned based on a percentage drop in performance, such as every 10-20% decrease in filtration efficiency, or based on time intervals, such as weekly or bi-weekly, depending on operational conditions.

5. Conclusions

The integrated H-UASB reactor coupled with ceramic membrane filtration demonstrated promising potential for the treatment of paper and pulp industry wastewater, particularly in balancing pollutant reduction with energy recovery. The overall treatment output revealed dynamic variations in influent and effluent concentrations, underscoring the system's sensitivity to fluctuations in wastewater characteristics and operational stability. While the reactor consistently achieved meaningful reductions in COD and TSS, the observed day-to-day variability highlights the importance of continuous monitoring and fine-tuning of operational parameters to sustain stable performance.

Biogas production rates ranged from 1.8 to 4.4 L/day, confirming the reactor's capacity for resource recovery through anaerobic digestion. These findings emphasize that under favourable conditions, the system not only contributes to pollutant reduction but also generates renewable energy, thereby supporting the principles of circular economy and improving overall process sustainability.

The ceramic membrane unit provided an additional polishing step, achieving COD removal efficiencies between 42.4% and 56.5% over the observation period. However, a gradual decline in efficiency pointed to fouling as a persistent operational challenge. COD and TSS values in the treated effluent reflected satisfactory performance initially, but progressive increases across subsequent days reinforced the need for systematic fouling control and optimized cleaning intervals.

Overall, the study establishes that the hybrid H-UASB–ceramic membrane system can deliver effective wastewater treatment and energy recovery in the paper and pulp sector. Nonetheless, its long-term viability hinges on three critical factors: (i) stabilization of reactor performance through optimized hydraulic and organic loading control, (ii) consistent enhancement of biogas yield through balanced microbial activity, and (iii) proactive management of membrane fouling via tailored cleaning protocols. Addressing these operational challenges will be central to scaling the system for industrial adoption and ensuring its role as a sustainable wastewater management solution.

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