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Integrated Analysis of Sludge Management and Biogas Production from COD Removal in Wastewater Treatment

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ABSTRACT: Sludge management is a critical aspect of wastewater treatment, particularly in industries such as pulp and paper, where high organic loads and suspended solids challenge system efficiency, operational costs, and sustainability. This study evaluates sludge generation, concentration, withdrawal frequency, and associated gas production through COD removal analysis of pulp and paper wastewater. The sludge volume was estimated using COD removal data, yielding approximately 0.04675 m³ per day at a solids concentration of 20,000 ppm. Sludge concentration was determined from influent and effluent COD differences, with values indicating effective organic matter removal. Gas production analysis revealed that COD removal directly correlates with biogas yield, with a calculated biogas volume of 0.32725 m³, comprising approximately 60% methane (0.196 m³) and 40% carbon dioxide (0.131 m³) under typical conditions. Gas collection efficiency was highlighted as a key parameter for assessing system performance. Operational factors such as current density, power consumption, and hydraulic retention time (HRT) were also analyzed, demonstrating their influence on COD removal efficiency and energy balance. The results emphasize the interdependence of sludge management and gas production in optimizing pulp and paper wastewater treatment, offering insights for improving energy recovery and ensuring sustainable plant operation.

KEYWORDS: Sludge management, Pulp and paper wastewater, COD removal, Hydraulic retention time (HRT), Sludge concentration, Biogas recovery, Sustainability

1. INTRODUCTION

Sludge is an inevitable by-product of municipal and industrial wastewater treatment processes, and its management has emerged as one of the most pressing environmental and operational challenges worldwide. Large volumes of sludge are generated daily, often containing high organic content, nutrients, heavy metals, and pathogenic organisms, which require careful handling to prevent environmental pollution and health risks. Among different industrial sources, the pulp and paper sector is one of the largest contributors to wastewater and sludge generation due to its intensive use of water, chemicals, and fibrous raw materials. Pulp and paper wastewater is characterized by high concentrations of lignin, cellulose fibers, chemical additives, and recalcitrant organic compounds, making sludge management in this sector particularly complex.

Conventional disposal methods, such as landfilling, incineration, and uncontrolled land application, are increasingly restricted due to regulatory, environmental, and economic constraints. In recent years, the focus of sludge management has shifted from disposal to resource recovery, aiming to transform sludge into a source of renewable energy and useful by-products. Anaerobic digestion (AD) is the most widely employed biological process in this context, as it not only stabilizes organic matter and reduces sludge volume but also generates biogas, a renewable fuel mainly composed of methane (CH_4) and carbon dioxide (CO_2). For pulp and paper sludge, pretreatment methods such as thermal hydrolysis and enzymatic treatment are often required to break down resistant compounds and improve biodegradability.

The efficiency of gas production depends on sludge characteristics, pretreatment methods, process configuration, and operational parameters. To optimize performance, techniques such as co-digestion with organic wastes and advanced monitoring and modeling (e.g., ADM1) are being explored. Therefore, sludge management and gas production analysis are closely interconnected research domains. Effective treatment strategies, particularly for pulp and paper waste, not only enhance energy recovery potential but also support compliance with environmental standards. This integration of waste valorization into treatment processes contributes to the development of sustainable wastewater treatment plants and supports the transition toward a circular economy.

2. LITERATURE SURVEY

Recent research highlights the promising role of Upflow Anaerobic Sludge Blanket (UASB) reactors in wastewater treatment and sustainable energy recovery. Mainardis et al. (2020) emphasize the emerging trends and prospects of UASB technologies, such as enhanced microbial understanding, mathematical modeling, and co-digestion strategies for maximizing biogas generation within a circular economy framework. Zielinski et al. (2022) further evaluate the advantages of anaerobic treatment, including space efficiency, high methane yields, and low sludge generation, while pointing to innovations like microwave-assisted enzyme activation and integration with microalgal biomass for nutrient removal. Jagaba et al. (2021) focus on the effect of hydraulic retention time on pulp and paper wastewater treatment, reporting significant COD, ammonia, and nitrate reductions with reliable compliance to discharge standards. Complementing these findings, Arthur et al. (2022) demonstrate the success of full-scale UASB reactors combined with trickling filters in Ghana, achieving high BOD (98%) and COD (93%) removal along with substantial biogas recovery. Collectively, these studies underline UASB reactors as efficient, sustainable, and adaptable technologies for industrial and municipal wastewater treatment, with strong potential to contribute to renewable energy generation and environmental protection, especially in developing regions.

3. Methodology

The Hybrid Up-Flow Anaerobic Sludge Blanket (HUASB) reactor improves sludge management by enabling wastewater to flow upward through an anaerobic sludge layer where microorganisms decompose organic matter without oxygen. The use of ceramic membranes enhances sludge–water separation, reduces fouling, maintains stable microbial density, and improves effluent quality. Baffles ensure better flow distribution, reducing short-circuiting and stabilizing pH and alkalinity, which supports effective sludge activity.

For gas production analysis, the reactor employs water displacement Mariotte's bottles to accurately measure biogas volume, providing essential data on microbial digestion and reactor efficiency. This systematic monitoring of COD, pH, alkalinity, and biogas generation helps assess treatment performance. Overall, the HUASB reactor demonstrates efficient sludge stabilization, improved effluent quality, and reliable biogas recovery, making it a sustainable option for pulp and paper wastewater treatment.

3.1 H-UASB reactor's working principle

The newly developed Hybrid Up-Flow Anaerobic Sludge Blanket reactor (HUASB) that has been incorporated in the advancement of wastewater treatment technology focuses on the treatment of high strength wastewater most probably emanating from the paper and pulp industries. It is a modern type of UASB process that has been upgraded with some additional performance aspects to meet enhanced performance. The process involved in the HUASB is shown in fig 3.1.

The HUASB-based treatment process begins with influent distribution and controlled pumping to maintain proper up-flow velocity, allowing wastewater to rise through the anaerobic sludge blanket where organic matter is degraded via hydrolysis, acidogenesis, acetogenesis, and methanogenesis into biogas and stabilized sludge. The reactor simultaneously produces three outputs: biogas, which is collected, conditioned, and converted for energy use; sludge, which is periodically withdrawn, dewatered, and either reused as inoculum or safely disposed; and treated effluent, which is stored in a collecting tank and further polished if required before final disposal. Effective operation relies on continuous monitoring of COD, BOD, pH, alkalinity, VFA/ALK ratio, solids, sludge blanket stability, and gas yield to ensure efficient energy recovery, sludge stabilization, and high-quality effluent discharge.

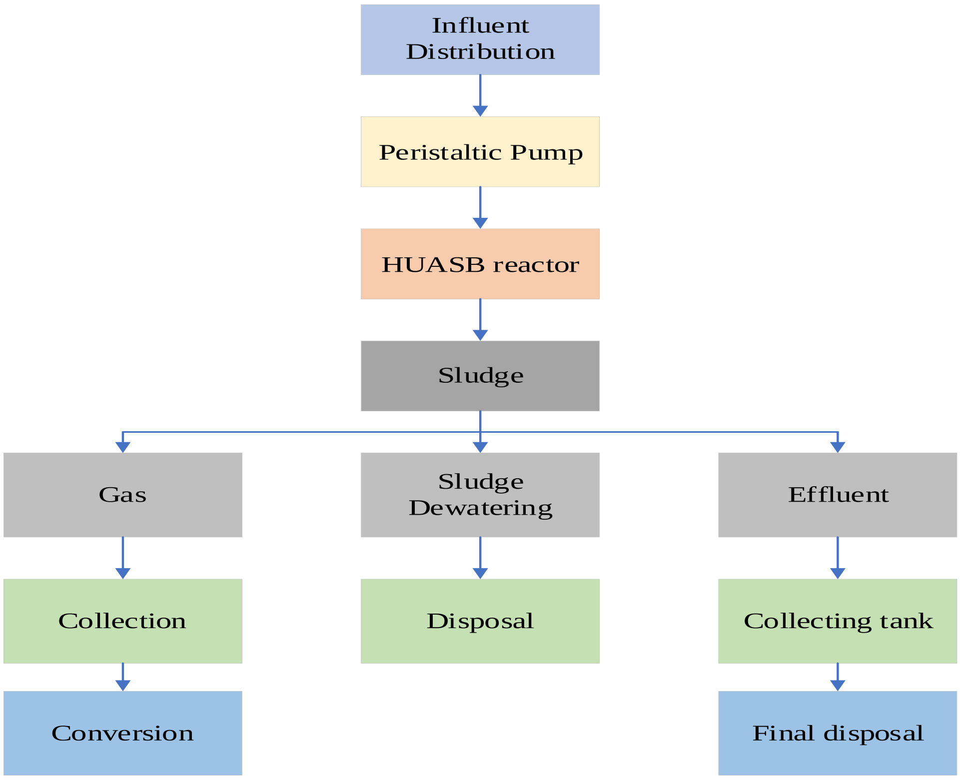

Fig 3.1 HUASB process

Fig 3.2 explains the Anaerobic Digester System and its resource recovery pathway:

- Inputs: Agricultural waste, wasted food, biosolids, and organic wastewater first go through pre-processing to remove contaminants and prepare feedstock.
- Anaerobic Digester: The prepared material undergoes anaerobic digestion, producing biogas and a solid/liquid effluent.
- Biogas Pathway: Biogas is cleaned through impurity removal and then used to generate electricity (e.g., engines), thermal energy (direct heat), or fuel (pipeline gas, vehicle fuel).
- Effluent Pathway: The digested residue is post-processed into:
  - Solid products like compost and animal bedding.
  - Liquid products such as organic fertilizers.

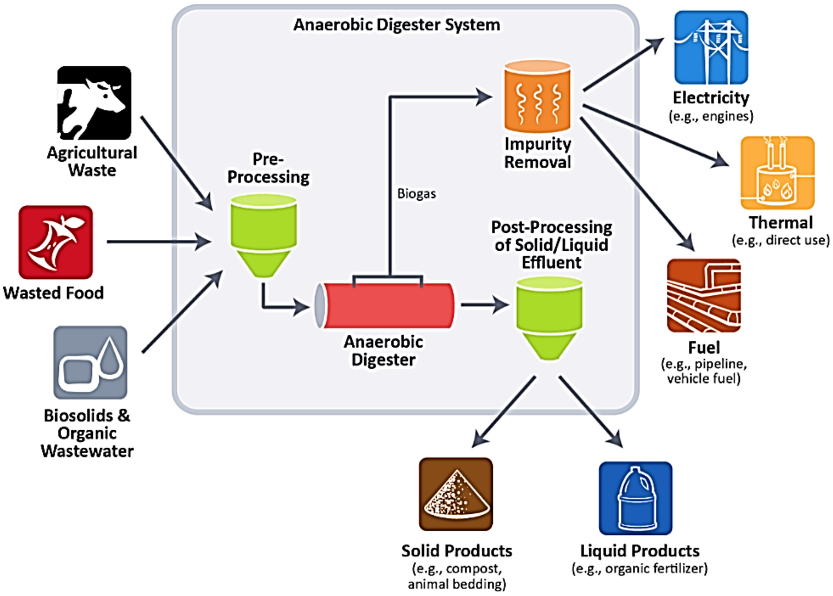

Fig 3.2 Anaerobic Digester System

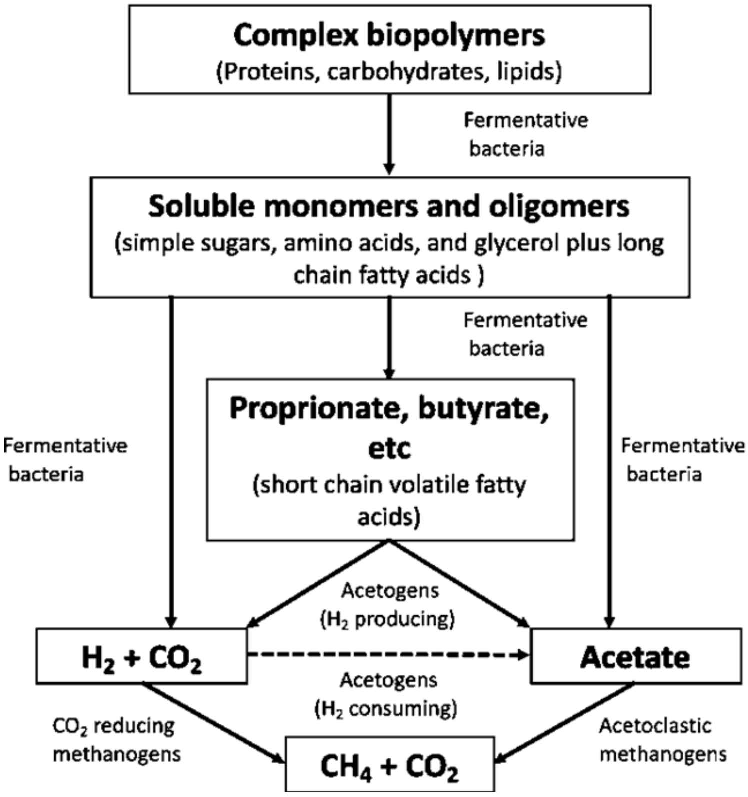

Fig 3.3 Production of methane and carbon dioxide by the bacteria

Fig 3.3 explains the biochemical pathways of anaerobic digestion leading to methane production:

1. Complex Biopolymers (proteins, carbohydrates, lipids) are hydrolyzed by fermentative bacteria into soluble monomers and oligomers (sugars, amino acids, glycerol, fatty acids).
2. These monomers are further fermented into volatile fatty acids (e.g., propionate, butyrate) by fermentative bacteria.
3. Acetogens then process these intermediates:
   - Some pathways produce $H_2 + CO_2$, used by hydrogenotrophic methanogens to form methane.
   - Others form acetate, which is directly converted to methane by acetoclastic methanogens.
4. The final step produces $CH_4 + CO_2$ (biogas).

4. RESULT AND DISCUSSIONS

4.1 Sludge Management

Sludge management in wastewater treatment systems can be approached through a detailed analysis of sludge volume, concentration, and withdrawal efficiency. To estimate the sludge volume, begin with the COD removal data, which provides insight into the amount of organic matter removed from the effluent. Assuming a typical concentration of solids in the sludge of approximately 20,000 ppm, the sludge volume using the formula:

$$\text{volume of sludge} = \frac{\text{Amount of COD Removed}}{\text{Concentration of Solids in Sludge}} \quad (4.1)$$

In this, with an initial COD concentration of 1100 ppm and a removal efficiency of 85%, the amount of COD removed is calculated as:

$$\text{COD Removed} = 1100\text{ppm} \times 0.85 = 935\text{ppm}$$

$$\text{Volume of Sludge} = \frac{935 \text{ ppm}}{20000 ppm} = 0.04675\text{m}^3$$

The sludge volume is approximately 0.04675 cubic meters, which provides a foundational understanding of the sludge generation in the system.

Sludge concentration, on the other hand, reflects the effectiveness of the treatment process and can be derived from the difference between influent and effluent COD concentrations. For example, on Day 1, with an influent COD concentration of 470.3 ppm and an effluent COD concentration of 219.05 ppm, the concentration of sludge can be calculated by Eq 4.2:

$$\text{Sludge Concentration} = \text{Influent COD} - \text{Effluent COD} \quad (4.2)$$

$$= 470.3\text{ppm} - 219.05\text{ppm} = 251.25\text{ppm}$$

This value indicates the amount of organic material present in the sludge, which is crucial for understanding the treatment efficiency and planning for sludge management strategies.

Sludge withdrawal frequency is a critical aspect of maintaining the efficiency of a wastewater treatment system. It depends on the system's design, including its capacity for handling sludge and the rate at which sludge accumulates. If the system generates approximately 0.04675 m^3 of sludge per day, sludge withdrawal may need to occur daily or weekly to prevent excessive accumulation. The frequency of withdrawal is typically based on operational factors such as the maximum allowable sludge volume and the rate of accumulation.

4.2 Gas Production Analysis

The results presented in the gas production analysis provide information about effectiveness of the treatment and the entire system. Hydrogen and oxygen are the major components of the produced gas and the volume and the composition of the gas depend on factors such as current density, electrode configuration and the operational conditions. Greater values of current density generally improve the rate of the electrochemical processes which may lead to enhanced generation of the gaseous product. However, this must be done in a way that the power consumption of the system is optimal to avoid high costs. It is crucial therefore to have continual checking of the production rate of the gas as well as its composition for enhancement of the treatment process in addition to operation effectiveness. Furthermore, the measure of the efficiency of the collected gases serves as an important factor that demonstrates the efficiency of the generated gases' collection and usage in the treatment system, which can affect the work of the system in general, as well as its sustainability.

4.2.1 Biogas Volume

To estimate the volume of biogas produced, we would typically use data on COD removal, as this is an indicator of the organic matter being converted into biogas. Assuming that the COD removal data is indicative of the biogas production, we can use the COD removal efficiency to estimate biogas volume.

For simplicity, assuming a typical conversion factor from COD removed to biogas volume. One common estimate is that 1 kg of COD removed can produce approximately 0.35 m^3 of biogas based on specific conditions. The calculation of biogas volume for each COD removal rate is follows. For an initial COD concentration of 1100 ppm with an 85% removal rate the COD Removed is 935ppm.

The volume of biogas can be approximated as:

Biogas Volume=COD Removed×0.35

Assuming the COD removed is 935 mg/L it is converted to kg for volume calculation.

Biogas Volume=0.935kg×0.35m^3/kg=0.32725m^3

4.2.2 Biogas Composition

Biogas typically comprises methane (CH_4) and carbon dioxide (CO_2), with trace amounts of other gases. The exact composition will depend on the feedstock and process conditions. In the absence of specific data, a general composition of biogas can be assumed as:

- Methane (CH_4): 50-70%
- Carbon Dioxide (CO_2): 30-50%
- Trace gases: <1%

Based on the typical biogas production, if the volume of biogas is 0.32725 m^3, the composition might be estimated as follows:

- Methane (CH_4): 0.32725 m^3×60%=0.19635 m^3
- Carbon Dioxide (CO_2): 0.32725 m^3×40%=0.1309 m^3

4.3.3 Gas Collection Efficiency

Gas collection efficiency measures how effectively the produced gas is captured relative to the total gas produced. This can be calculated if we know the actual volume of gas collected versus the theoretical volume. The formula for gas collection efficiency is in equation 4.4.

$$\text{Gas Collection Efficiency} = \frac{\text{Total Volume of Gas Produced}}{\text{Volume of Gas Collected}} \times 100\% \quad (4.4)$$

4.3 Operational Parameters

The parameters that directly affect the speed of operation of the wastewater treatment process such as the current density, the power consumption and hydraulic retention time are crucial for the functioning of the whole system. Fluctuations in current density affect the rate of chemical reactions with a direct relevance to the levels of COD reduction and power consumption. Although generally, higher values of current density improve removal rates in addition to energy consumption, which might be crucial for the selection of the right balance with reference to cost. The measurements of power consumption give information regarding energy intake by the system and is significant for the analysis of efficiency. Also, there is the dimension known as HRT, which defines the number of days that wastewater stays in the system before receiving a particular level of treatment. Ideal operating conditions for HRT allow for adequate contact time for the contaminants to be cleared out of the water but not to the extent of wastage of energy. These parameters need to be controlled in a way that the treatment efficiency and cost as well as the outflow quality is optimised.

4.3.1 Hydraulic Retention Time (HRT)

Hydraulic Retention Time (HRT) is a key parameter in wastewater treatment, indicating the average time that wastewater remains in the treatment system. It is calculated using the equation 4.3.

$$\text{HRT} = \frac{\text{Flow Rate}}{\text{Volume of Reactor}} \quad (4.3)$$

Given the data for different days, HRT is already provided:

Day 1: HRT = 8 hours
Day 2: HRT = 10 hours
Day 3: HRT = 12 hours
Day 4: HRT = 16 hours
Day 5: HRT = 24 hours

The values indicate how long the influent wastewater stays in the reactor, which affects the efficiency of treatment.

4.3.2 Influent and Effluent Flow Rates

To determine the influent and effluent flow rates, we use the given COD concentrations and HRT values. For this, we assume that the reactor volume remains constant, and we can estimate flow rates based on COD removal and HRT.

For each day, using the formula:

$$\textbf{Flow Rate} = \frac{\text{Volume of Reactor}}{\text{HRT}} \quad (4.4)$$

To estimate the reactor volume, we can use a standard approximation based on COD data. Assuming a reactor volume of 10 m^3 , the flow rate for each day is calculated as follows:

Day 1: HRT = 8 hours

Flow Rate= 1.25 m^3/hour

Day 2: HRT = 10 hours

Flow Rate =1.0 m^3/hour

Day 3: HRT = 12 hours

Flow Rate = 0.83 m^3/hour

Day 4: HRT = 16 hours

Flow Rate = 0.625 m^3/hour

Day 5: HRT = 24 hours

Flow Rate = 0.417 m^3/hour

Here's a **Conclusion** section based on the sludge management and gas production analysis you provided:

5. Conclusions

The study highlights the crucial link between sludge management and gas production in wastewater treatment systems. By applying COD removal data, sludge volume was quantified at approximately 0.04675 m^3 per day, providing a reliable estimate of sludge accumulation for withdrawal planning. Sludge concentration values derived from influent and effluent COD differences confirmed effective removal of organic matter, demonstrating the system's treatment efficiency.

Gas production analysis showed that COD removal directly translates into biogas generation, with an estimated yield of 0.32725 m^3 per day, comprising around 60% methane and 40% carbon dioxide. This underscores the energy recovery potential of anaerobic processes when operated under optimal conditions. Additionally, gas collection efficiency was identified as a critical operational factor for maximizing energy utilization and overall process sustainability.

Operational parameters, including current density, power consumption, and hydraulic retention time (HRT), were found to significantly affect both treatment performance and energy balance. Proper adjustment of these parameters can enhance COD removal, improve sludge stabilization, and increase gas yield, while maintaining cost-effectiveness.

Overall, the findings demonstrate that integrated sludge management and gas production analysis not only improve treatment efficiency but also support renewable energy recovery, contributing to the sustainability of wastewater treatment plants. Future work should focus on optimizing operational conditions, improving gas capture technologies, and conducting long-term performance assessments at pilot and full scale.

REFERENCES

1. Mainardis, M., Buttazzoni, M., & Goi, D. (2020). Up-flow anaerobic sludge blanket (UASB) technology for energy recovery: a review on state-of-the-art and recent technological advances. Bioengineering, 7(2), 43.
2. Zieliński, M., Kazimierowicz, J., & Dębowski, M. (2022). Advantages and limitations of anaerobic wastewater treatment—technological basics, development directions, and technological innovations. Energies, 16(1), 83.
3. Jagaba, A. H., Kutty, S. R. M., Fauzi, M. A. H. M., Razali, M. A., Hafiz, M. F. U. M., & Noor, A. (2021, August). Organic and nutrient removal from pulp and paper industry wastewater by extended aeration activated sludge system. In IOP conference series: Earth and environmental science (Vol. 842, No. 1, p. 012021). IOP Publishing.
4. Arthur, P. M., Konaté, Y., Sawadogo, B., Sagoe, G., Dwumfour-Asare, B., Ahmed, I., & Williams, M. N. (2022). Performance evaluation of a full-scale up-flow anaerobic sludge blanket reactor coupled with trickling filters for municipal wastewater treatment in a developing country. Heliyon, 8(8).
5. Tawfik, A., Bakr, M. H., Nasr, M., Haider, J., Lim, H., Qyyum, M. A., & Lam, S. S. (2022). Economic and environmental sustainability for anaerobic biological treatment of wastewater from paper and cardboard manufacturing industry. Chemosphere, 289, 133166.
6. Mainardis, M., Buttazzoni, M., & Goi, D. (2020). Up-flow anaerobic sludge blanket (UASB) technology for energy recovery: a review on state-of-the-art and recent technological advances. Bioengineering, 7(2), 43.
7. Mazhar, M. A., Khan, N. A., Khan, A. H., Ahmed, S., Siddiqui, A. A., Husain, A., ... & Radwan, N. (2021). Upgrading combined anaerobic-aerobic UASB-FPU to UASB-DHS system: cost comparison and performance perspective for developing countries. *Journal of Cleaner Production*, *284*, 124723.
8. Engida, T. M., Wu, J. M., Xu, D., & Wu, Z. B. (2020). Review paper on the treatment of industrial and domestic wastewater using UASB reactors integrated into constructed wetlands for sustainable reuse. *Applied Ecology & Environmental Research*, *18*(2).