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Design and optimization of molasses-based wastewater treatment plant at Agro-Chemical and Food Company Limited (ACFC), Muhoroni, Kenya

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Abstract

The study aimed to design and optimize a treatment train for molasses-based wastewater at the Agro-Chemical and Food Company Limited (ACFC) in Muhoroni, Kenya. Raw influent parameters in the system were: Biochemical Oxygen Demand (BOD)-43,000mg/l, Chemical Oxygen Demand (COD)-120,000mg/l, Total Suspended Solids (TSS)-95,000mg/l, pH-4.25, and Temperature-40°C. The existing wastewater treatment plant comprises of an Anaerobic Digester, Bulk Volume Fermenter and Aerated lagoons. Optimization of anaerobic digester is done through design based on Hydraulic Retention Time (HRT) and is expected to achieve a biogas production rate increase of 49.71% on average. To ensure the plant complies with National Environment Management Authority (NEMA) standards, an upgrade of the existing system will be done by retrofitting Aeration Tanks and Secondary Clarifiers. These findings support scale-up and offer a replicable framework for agro-industrial wastewater management. The results of the study showed that implementing the optimal conditions and incorporating the aeration tanks and secondary clarifiers will result in about a 50% reduction of fuel cost by utilizing the biogas produced and meeting the wastewater effluent standards respectively.

Keywords: Anaerobic Digester Optimization; Biochemical Oxygen Demand (BOD); Biogas; Chemical Oxygen Demand (COD); Effluent Compliance; Molasses Wastewater

1. Introduction

Industrial plants like Agro-Chemical and Food Company Limited (ACFC) generate a significant amount of high-strength wastewater. Molasses-based wastewater is the high-strength effluent generated primarily by sugar production facilities that use molasses as a feedstock. It is also referred to as spent wash in distillery operations. This wastewater typically exhibits extremely high organic loads; the effluent is characteristically dark brown due to complex, recalcitrant pigments such as melanoidin formed during sugar processing [4]. It also has a low pH, reflecting its acidic nature, and high concentrations of nutrients, i.e., nitrogen, phosphorus, and potassium, which lead to eutrophication if discharged untreated. In addition to organic and nutrient pollution, its high suspended-solid content and color impede light penetration and aquatic photosynthesis. Due to these properties, molasses wastewater is classified as "high-strength industrial wastewater" and requires specialized anaerobic and/or aerobic treatment processes to meet discharge standards. Anaerobic digestion offers a low-cost treatment route that simultaneously generates biogas, but its performance hinges on optimal operating conditions such as temperature, pH, and hydraulic retention time. Various treatment methods for molasses-based wastewater have been explored, though several literature gaps persist that hinder the development of efficient and sustainable treatment solutions.

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Although individual treatment methods like anaerobic digestion, aerobic processes, and advanced oxidation have been studied, there is inadequate comprehensive research on the integration and optimization of these methods for molasses-based wastewater [9]. Studies on the synergistic effects of combined treatments, such as anaerobic-aerobic sequencing or coupling biological processes with advanced oxidation, are limited. Molasses wastewater contains complex compounds like melanoidin and polyphenols that are resistant to conventional biological treatments. There is a need for more research into effective methods for degrading these recalcitrant substances. Many existing treatment methods are energy-intensive and costly, making them less feasible for small to medium-sized enterprises. Research into low-cost, energy-efficient treatment technologies is still emerging and requires further exploration. The dynamic nature of molasses wastewater composition necessitates real-time monitoring and adaptive control strategies. However, literature on the development and implementation of real-time monitoring systems for such wastewater is scarce. While the potential for resource recovery from molasses wastewater (e.g., biogas, bio-fertilizers, or biofuels) is recognized, practical applications and pilot studies demonstrating the feasibility and efficiency of such valorization processes are limited.

This research and design embark on a comprehensive evaluation and enhancement of a treatment plant for molasses-based wastewater. Initial benchmarking revealed that, although the existing anaerobic digester achieved appreciable biogas production, effluent COD and BOD levels frequently exceeded discharge standards. To address this, a detailed performance assessment of key parameters such as pH, temperature, TSS, BOD and COD was conducted to quantify the plant's baseline efficiency. Building on these insights, process optimizations in the anaerobic digester were done, which are expected to increase biogas production and overall organic removal. Finally, to ensure compliance with effluent criteria the system is to be retrofitted, between the bulk volume fermenter and the aerated lagoons, with aeration tanks and secondary clarifiers which provide a comprehensive treatment approach and ensures the production of a high-quality effluent that complies with environmental discharge standards. For this study, while focusing on ACFC, Muhoroni, Kenya, the main objective and specific objectives were as follows: -

1.1. Main Objective

To design and optimize a molasses-based wastewater treatment plant at Agro-Chemical and Food Company Limited, Muhoroni.

1.1.1. Specific Objectives

- To characterize molasses-based wastewater.
- To determine the efficiency of a molasses-based wastewater treatment system.
- To optimize the anaerobic digester through design.
- To upgrade the ACFC wastewater treatment plant to comply with effluent standards.

2. Data Used and Methodology

To fulfill the aim of the research and study, the molasses-based wastewater was characterized by considering mainly BOD, COD, TSS *(all these were carried out as per the APHA standards)* [1], temperature and pH *(using thermometer and pH meter respectively)*. Grab sampling method and the composite sampling method were used. The focus was on the following samples: influent to the anaerobic digester, effluent from the anaerobic digester, influent and effluent from the aerated lagoons.

2.1. BOD test

The method consists of filling an airtight bottle of the specified size and incubating it at the specified temperature for 5 days. Dissolved oxygen is measured initially and after incubation, and the BOD is computed from the difference between the initial and final DO. Because the initial DO is determined shortly after the dilution, all oxygen uptake occurring after this measurement is included in the BOD measurement. BOD at all points was determined from the following formula:

$$BOD = (\text{Final day titre value} - \text{Initial day titre value}) \times F$$

Where:

Titre value	-	Value of Sodium Thiosulfate consumed.
F	-	Sample dilution factor.

2.2. COD test

Multiple approved procedures for determining COD as per the APHA standard method are via open-flux, closed–reflux titrimetric, or closed-reflux calorimetric techniques [1]. The open reflux method is suitable for a wide range of wastes where a large sample size is preferred. The closed reflux methods (Titrimetric and Calorimetric) are more economical in the use of metallic salt reagents and generate smaller quantities of hazardous waste but require homogenization of samples containing suspended solids to obtain reproducible results. Ampules and culture tubes with premeasured reagents are available commercially. Measurements of sample volumes as well as reagent volumes and concentrations are critical. For this case, the open flux method was used, where most types of organic matter are oxidized by a boiling mixture of chromic and sulfuric acids. A sample is refluxed in a strongly acidic solution with a known excess of potassium dichromate ($K_2Cr_2O_7$). After digestion, the remaining unreduced $K_2Cr_2O_7$ is titrated with ferrous ammonium sulfate to determine the amount of $K_2Cr_2O_7$ consumed and the oxidizable matter is calculated in terms of oxygen equivalent. The standard 2-hour reflux time may be reduced if it has been shown that a shorter period yields the same results. After the test, COD was obtained using the following formulae.

$$\text{COD (mg } O_2\text{/L)} = \frac{[\,(A-B)\times M\times 8000]}{V}$$

Where

A	-	mL FAS used for blank
B	-	mL FAS used for the sample
M	-	Molarity of FAS
V	-	Volume of sample used
8000	-	Milliequivalent weight of oxygen × 1000 mL/L
FAS	-	Ferrous Ammonium Sulfate

2.3. TSS test

A suspended solid is the term used to describe particles in the wastewater or water column. They are particles large enough not to pass through the filter being used to separate them from the sample. Methods available for the determination of suspended solids are the filter paper method [5] and the spectrophotometer method [6]. For the filter paper method, a well-mixed sample is filtered through a weighed standard glass-fiber filter, and the residue retained on the filter is dried to a constant weight at 103 to 105°C. The increase in weight of the filter represents the total suspended solids. If the suspended material clogs the filter and prolongs filtration, it may be necessary to increase the diameter of the filter or decrease the sample volume. The spectrophotometric TSS method measures the absorbance or turbidity of a homogenized water sample at a selected wavelength. The loss of light intensity is proportional to the concentration of particles in suspension. The instrument directly reports TSS in mg/L once calibrated against standards. After using the filter paper, the following formula was used.

$$\text{mg total suspended solids/L} = \frac{(A-B)\times 1000}{\text{Sample Volume, mL}}$$

Where

A	-	Weight of filter + dried residue, mg
B	-	Weight of filter, mg

2.4. Efficiency of molasses-based wastewater treatment system

After gathering influent and effluent data for the key parameters mentioned above for each existing unit, i.e., anaerobic digester, bulk volume fermenter and aerated lagoons, removal efficiencies (%) for each parameter in each unit were obtained using the following formulae.

$$\text{Removal efficiency} = \left(\frac{\text{Influent Concentration} - \text{Effluent Concentration}}{\text{Influent Concentration}}\right)\times 100\%$$

2.5. Optimization of anaerobic digester through design

The optimal conditions for maximizing biogas production were obtained iteratively by adjusting key operational parameters: pH, Hydraulic Retention Time (HRT) and Temperature. The design is based on hydraulic retention time [3]. The variables were pH (constrained between 6.5 and 8), HRT (limited to 17–22 days), and Temperature (restricted to 30–40°C). The biogas production rate, serving as the objective function, was modeled using a regression equation linking the three variables to gas output [11]. According to [8], COD removal rates in well-operated anaerobic digesters range between 68.6-93.7% and was set to 80%(average) for this case.

$$\text{Biogas Produced } (m^3/\text{KgCOD removed}) = \frac{-224{\cdot}562 + 2{\cdot}481T + 44{\cdot}471(pH) + 9{\cdot}013(HRT) + 0{\cdot}001T(HRT) - 0{\cdot}075(pH)(HRT) - 0{\cdot}037T^2 - 3{\cdot}079(pH)^2 - 0{\cdot}258(HRT)^2}{100}$$

$$\text{Methane}(\%) = \frac{-27543{\cdot}704 + 307{\cdot}741T + 5429{\cdot}167(pH) + 1114{\cdot}881(HRT) + 0{\cdot}095T(HRT) - 9{\cdot}286(pH)(HRT) - 4{\cdot}637T^2 - 375{\cdot}833(pH)^2 - 31{\cdot}854(HRT)^2}{100}$$

Where

T	-	Temperature, ˚C
HRT	-	Hydraulic Retention Time, days

This systematic approach successfully identified the ideal operational parameters (pH, HRT, and Temperature) for peak biogas yield (m^3/kg COD removed) while adhering to practical constraints.

2.6. Upgrade of ACFC wastewater treatment plant to comply with effluent standards

After optimization of the anaerobic digester, additional units were considered that would reduce the concentration of organic load. In this study, the activated conventional sludge process was the most viable method. The conventional activated sludge (CAS) process is a suspended growth, an aerobic biological treatment method widely used for secondary treatment of municipal and industrial wastewater [2]. It employs aerobic microorganisms to biodegrade organic matter in wastewater within an aeration tank, followed by solids–liquid separation in a secondary clarifier. The process relies on recycling a portion of settled biomass (return activated sludge) to maintain microbial populations and achieve effluent quality targets for BOD and TSS. Wastewater first undergoes preliminary screening to remove large debris before entering the aeration tank, where oxygen is supplied to support microbial degradation of organic pollutants. After sufficient contact time, mixed liquor flows into a secondary clarifier that separates biomass from the treated effluent by gravity. A portion of the settled sludge is returned to the aeration tank as Return Activated Sludge (RAS) to sustain a high concentration of microorganisms, while excess sludge is wasted for further treatment and disposal [7].

A methodical approach was used in designing the entire mixed-activated sludge process. Data on influent wastewater, including flow rate (Q), required effluent quality (S_e), TSS, and BOD_5 (S_0), were first obtained. Sludge retention time (SRT), food-to-microorganism ratio, and MLSS concentration were among the operational parameters chosen. While keeping DO ≥ 2 mg/L, the aeration tank volume and aeration requirements were computed based on oxygen demand, considering sludge degradation and BOD removal.

With a depth of 3–5 meters, the secondary clarifier was designed based on surface overflow rates and solids loading rates. The rates of sludge recycling (Return Activated Sludge (RAS), 25–100% of Q) and Waste Activated Sludge (WAS) were modified to preserve the intended SRT. Effluent quality was checked for TSS and BOD_5 compliance. The final design output included the expected effluent concentrations, clarifier size and aeration tank dimensions.

3. Results

3.1. Wastewater Characterization

The molasses-based wastewater exhibited the following characteristics for the raw wastewater and the treated effluent which was being released to the environment.

Table 1 Molasses-Based Wastewater Characteristics

Parameter	Units	Raw wastewater	Treated effluent
BOD	mg/L	43,000	300
COD	mg/L	120,000	4,000
TSS	mg/L	95,000	543
pH	-	4.25	8.5
Temperature	˚C	40	22

3.2. Efficiency of the treatment system

After determination of wastewater characteristics of the existing units, in terms of BOD, COD and TSS removal, the efficiencies were obtained as shown below.

Table 2 Individual Units Removal Efficiency

Parameter	Treatment unit		
	Removal efficiencies (%)		
	Anaerobic digester	Bulk volume fermenter	Aerated lagoons
BOD	81.86	70.51	86.96
COD	53.33	78.04	67.48
TSS	98.11	50.17	39.46

Table 3 Overall Removal Efficiencies Based on Raw Wastewater and Effluent Released to the Environment

Parameter	Removal efficiency (%)
BOD	99.30
COD	96.67
TSS	99.43

3.3. Optimization of anaerobic digester

Upon iteratively modifying the input variables within the specified limits to identify the combination yielding the highest biogas production rates, the optimal conditions of the anaerobic digester were obtained as pH-7.01, temperature - 33.76 °C, and HRT-17 days. This is expected to achieve a biogas production yield of 39107.71 m^3/d. The COD removal rate is expected to rise to 80%.

3.4. Upgrade of the plant system

Two aeration tanks measuring 18.1m x 9.1m x 3m deep have been provided. The BOD_5 concentration in the effluent is about 62.5 mg/L which is a 93.5% removal rate. Two clarifiers measuring 5.5m Diameter x 3m deep have been provided achieving BOD_5 concentration in the effluent of 43.77 mg/L which is a 30% removal rate.

Implementation of the aeration tanks and clarifiers in the treatment system at ACFC, Muhoroni plant achieves steady-state effluent quality: BOD of 17 mg/L, COD of 47mg/L and TSS of 26mg/L after treatment in the aerated lagoons, thus meeting NEMA standards.

Table 4 NEMA Standards for Effluent Discharge into the Environment [10]

PARAMETER	UNITS	NEMA Requirement (Maximum)
BOD	mg/L	30
COD	mg/L	50
TSS	mg/L	30

4. Discussion

The raw molasses-based wastewater exhibited high organic waste thus the need for a robust anaerobic stage to prevent reactor overloading. The observed COD/BOD ratio of 2.791 indicates a substantial fraction of slowly biodegradable waste, thus requiring enhanced pre-treatment strategies and optimal working conditions of treatment. The influent pH averaged 4.25, falls below the optimal condition of 7.01 for methanogenic activity and would necessitate neutralization to maintain digesting stability. High TSS contributed to increased viscosity and poor oxygen transfer, justifying the inclusion of a secondary clarifier with a low overflow rate to improve sludge settling ability.

The anaerobic digester achieved 82% BOD removal, 53% COD removal, and 98% TSS removal at an HRT of 28 days before optimization. The high solids reduction is attributed to effective hydrolysis and methanogenesis under stable pH and mesophilic conditions. In the bulk volume fermenter, 78% COD and 71% BOD removal were observed before the optimization of the anaerobic digester. This corresponds with the literature value of 70 – 90% for BOD and COD reduction. The aerated lagoons realized 87% BOD and 39% TSS removal, these results vary with the 70–93% BOD and 60–85 %TSS removal reported for well-operated aerated lagoons. Collectively, these findings confirm the need for optimized units to achieve consistent compliance with effluent standards.

Under optimized conditions of pH - 7.01, temperature - 33.76 °C, and HRT - 17 days, a biogas yield of 39107.71 m^3/d is expected, representing an increment in biogas production of 49.71% from the average produced. This enhancement helps to maintain a neutral pH that favors methanogens, as shown in similar mesophilic systems treating sugar-rich waste. The aeration tanks achieved 94% BOD removal and 85% TSS removal while the clarifiers removed 30% and 70% BOD and TSS respectively. Following the retrofit, the combined aeration tanks and secondary clarifiers system improved the BOD, TSS and COD removal, thus meeting the NEMA effluent requirements.

5. Conclusion

This study set out to design and optimize a treatment train for molasses-based wastewater at the Agro-Chemical and Food Company Limited (ACFC) in Muhoroni, Kenya, with four core objectives: (1) to characterize the molasses-based wastewater, (2) to evaluate treatment efficiency of the existing system, (3) to optimize an anaerobic digester through design, and (4) to propose upgrades ensuring effluent compliance with NEMA standards. These findings confirm that the combined aerobic and anaerobic treatment train substantially reduces organic pollutants in molasses wastewater and offers energy-recovery benefits. The findings provide a scalable model for similar agro-industrial facilities with high-strength organic effluents, aligning with circular economic principles and regulatory requirements.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflict of interest to be disclosed.

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