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Impact of Different RPM on BOD, COD and Turbidity Reduction Using Natural and Synthetic Media in Dairy Wastewater Treatment

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ABSTRACT

This study lays the foundation for an integrated and adaptive method for treating dairy wastewater within a multi-stage Rotating Biological Contactor (RBC) system. Rotational speed optimization from stage to stage, dynamic control of hydraulic retention time (HRT), and better media performance evaluation are the ingredients drawn into the proposed model for the efficient removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and turbidity. Each RBC stage works with pollutant-specific RPM levels, that is, at the maximum biofilm interaction and pollutant reduction. HRT adjustments in real-time work via feedback mechanisms, whereas biofilm attachment is optimized through shear stress and media characteristics. The aim of this study was to demonstrate through comparative experiments that both natural (coconut coir) and synthetic (polyethylene) media can result in high biofilm growth and pollutant degradation rates. Robustness tests under varying influent loads indicated the same steady performance of the system. The integrated model achieved BOD removal of 90.1%, COD reduction of 85.3%, and turbidity removal of 79.8%. The final effluent quality is stringent as it meets discharge limits, with BOD<10 mg.L^{-1}, COD<50 mg.L^{-1}, and turbidity<10 NTU. The proposed framework presents an efficient and scalable option for the treatment of high-strength dairy effluents and can be deployed in several additional industrial waste scenarios.

INTRODUCTION

Dairy wastewater has relatively high organic loads, turbidity, and variable composition. Effluent with elevated BOD, COD, and suspended solids levels requires effective treatment before it can be released into natural water bodies. Traditional wastewater treatment systems (Katare et al. 2024, Katare et al. 2024, Ogedey et al. 2024) tend to reach their limitations in the management of the dynamic nature of dairy effluents, especially concerning the consistency in pollutant reduction levels across several parameters in the process. Although Conventional Rotating Biological Contactors have been established to be effective in industrial wastewater treatment, their performance under operation is significantly affected by critical variables such as rotational speed, hydraulic retention time (HRT), and biofilm attachment media. If not optimized, such factors will lead to biofilm instability, suboptimal reduction of pollutants, and inefficiencies in the treatment process. Although many studies have explored various configurations of RBCs, most existing systems are devoid of stage-wise optimization of operational parameters. Most approaches (Cargnin et al. 2024, Belkodia et al. 2024, Elkady et al. 2024) overlooked biofilm dynamics, the interdependence of shear stress, and pollutant-specific treatment efficiencies. The choice of medium, whether natural or synthetic, also heavily influences biofilm development and pollutant removal, although comparative studies are still in their infancy. The treatment technologies that advance possess a real need for solutions for both the improvement of removal of BOD, COD and turbidity, and for adaptation to changing wastewater compositions. Effective provision is also an integral component in achieving stringent discharge standards by providing effective residual pollutant-removing post-treatment units. This study aims to fill such gaps by introducing a novel multifaceted approach for the treatment of dairy wastewater using multiple-stage RBCs. The proposed framework optimizes the rotational speed, media type, and HRT at each stage of the RBC for progressive pollutant reduction. Complementary methods, such as feedback-based HRT control, media performance evaluation, and shear stress analysis, were incorporated into the system for enhanced robustness and efficiency. Post-treatment units with sedimentation and filtration are added to improve the quality of the effluent. Combined, these strategies not only demonstrated improved pollutant reduction performance but also established a scalable model for industrial wastewater treatment.

Motivation and Contribution

This study was motivated by the urgent need to optimize the efficiency of dairy wastewater treatment systems. Currently, existing technologies are hampered by the lack of interaction between key operational parameters and their combined effects on pollutant removal. Rotating speed, HRT, and media type have been analyzed as separate factors with inevitable suboptimal designs and inconsistent performance. Dynamic dairy wastewater has fluctuating levels of BOD, COD, and turbidity, which requires adaptive treatment strategies that can be maintained under realistic conditions. These challenges necessitate the development of an integrated approach consisting of multiple optimization techniques, where system robustness must be maintained across variable influent compositions. The principal contribution of this study is the development of an integrated framework for dairy wastewater treatment using multistage RBCs. The rotational speeds were optimized at different stages to ensure that the targeted pollutants were removed at each RBC stage, depending on the requirements of BOD, COD, and turbidity. Introduction of HRT-Based Adaptive Biofilm Stimulation and RPM-Shear Correlation for Biofilm Stability Improves Operational Flexibility and Integrity: Critical Areas Missing in Standard RBC Designs. Media selection can be an informed choice by comparing the differences between natural and synthetic media, whereas post-treatment units will contribute to meeting effluent quality standards. Real-world variability testing verified the resilience and scalability of the system. These contributions, in aggregate, form a comprehensive model for the treatment of dairy wastewater by creating high efficiency in managing industrial effluents.

In-Depth Review of Models Used for Wastewater Analysis

A review of the latest research on wastewater treatment indicates crucial advances in technology and methodology for industrial, agricultural, and domestic uses. Taken together, the surveys reviewed provide a broad view of current practices, innovative processes, and challenges in the treatment of complex effluents. Each paper in its own turn contributes to an understanding of wastewater treatment, but together they mark trends, limitations, and possible future directions of the research. Katare et al. (2024) studied the electrocoagulation of oil-field-produced water containing large amounts of COD, BOD, and turbidity. These reductions may have a significant impact on both the oil and gas industries. Ikhlaq et al. (2024) researched the catalytic ozonation of pharmaceutical wastewater and attained considerable effectiveness in removing persistent compounds such as enrofloxacin. Ogedey & Oguz et al. (2024) applied electrocoagulation to landfill leachate and attributed its effectiveness in treating combined COD and ammonia-nitrogen levels.

Cargnin et al. (2024) developed an integrated biological and physicochemical approach for shrimp farm wastewater with thorough contaminant removal. The treatment of cheese wastewater by Belkodia et al. (2024) through the application of advanced oxidation processes highlights the utility of integrated methodologies in developing approaches toward reuse standards for the irrigation process. Elkady et al. (2024) used carbonized sawdust and textile filtration in the treatment process for slaughterhouse wastewater, thereby underlining material reusability. Among the various wastewater and effluent treatment alternatives, Ahsan et al. (2023) specifically challenged the removal of dyes from textile wastewater, while Gholami et al. (2024) highlighted microalgae biofilters as an alternative for sustainable urban effluent treatment. Vermifiltration techniques applied to domestic wastewater (Kumar & Khwairakpam 2024) showcased the ecological advantages of biological processes. Ettaloui et al. (2023) used a sequence batch reactor for the treatment of oil washing wastewater with high efficiency under controlled environmental conditions. Ashar et al. (2024) investigated catalytic thermolysis as an advanced hybrid treatment process for textile wastewater and provided simple, scalable views of the process. Baghizade et al. (2023) considered biological treatment after flocculation, and Vezar et al. (2024) emphasized the use of natural bio-coagulants, such as papaya seeds, in the wastewater treatment of laundry. Lory et al. (2024) proposed microbial fuel cells for wastewater treatment, achieving pollutant removal and energy generation simultaneously. Bhuvanendran et al. (2024a) considered dairy wastewater by incorporating natural coagulants and product recovery. Katare et al. (2023) reviewed activated sludge processes for pharmaceutical effluents, with an emphasis on adaptability to many contaminant profiles. Constructed wetlands using *Pistia stratiotes* for domestic wastewater were presented by Ali et al. (2024), showing eco-friendly scalability. Mao et al. (2024) reviewed floating wetlands and highlighted the application of such systems in industrial wastewater treatment. (Das and Paul et al. 2023) have explored the scopes of treatment of dairy wastewater, with a discussion on the promising technique of peroxi-electrocoagulation and are studied further by Bhuvanendran et al. (2024b) and Dey and Pal et al. (2023) proposed the scope for the sustainable treatment potential of tannery effluents in a recent study on cyanobacteria.

Iteratively, as per Table 1, Radeef et al. (2024) integrated microbial fuel cells with biofilters for kitchen wastewater samples. Selvaraj and Arivazhagan et al. (2024) optimized textile treatments using electrocoagulation and adsorption with the help of advanced statistical tools for better results. The synthesis of nanoparticles for wastewater treatment, as demonstrated by Maloma et al. (2023), has antimicrobial benefits in addition to pollutant removal. Similarly, Thomas et al. (2023)applied neural networks to optimize laccase production and enhance dye removal. For instance, Elhadeuf et al. (2023) successfully optimized textile effluent treatment using electrocoagulation and microfiltration, while Fotoohi et al. (2024) attempted ultraviolet disinfection of biological systems. Cherni et al. (2024) investigated the treatment of rural wastewater using TiO_2-based photo-Fenton processes. Bedane and Asfaw (2024) showed hybrid anaerobic reactors coupled with microalgae for slaughterhouse wastewater and focused significantly on synergistic systems. Ayhan et al. (2024) and Mohan et al. (2024) analyzed different industrial applications, ranging from petroleum refinery effluents to graywater. In contrast, Kumari et al. (2024) discussed in detail several techniques for dye removal and presented future prospects. Benbouzid et al. (2024) used natural porous media for domestic wastewater, just like the sustainable approaches by Nzeyimana & Mary's (2024) that used Moringa oleifera. Yadav et al. (2024) and Sandhya Rani et al. (2023) referred to an advanced trend of applying advanced filtration technologies for coke oven and rubber-processing wastewater. Photocatalytic processes for petrochemical wastewater, as studied by Aghazadeh et al. (2023), showed novel proxone techniques. Detho et al. (2023) applied zeolite-based adsorbents for ammonia and COD reductions in rubber effluents.

Circular economy-based valorization of boiler ash to produce coagulant (Dalmora et al. 2024, Monroy-Licht et al. 2024) emphasized the application of phytoremediation with water hyacinth, while Boraghi et al. (2023) applied sinusoidal electrocoagulation along with ceramic filters for complete removal of pollutants. Nano-adsorbents of chitosan have been used to treat dairy effluent (Dinesha et al. 2023), opening up new horizons in the adoption of methodologies during the adsorption process. This holistic review of recent articles outlines the richness, diversity, and innovation of wastewater treatment technologies. This reflects the

Table 1: Comparative analysis of existing methods.

Method	Application	Key Findings	References
Electrocoagulation	Oil-field produced water	Achieved substantial COD, BOD, and turbidity reduction; scalable and efficient for high-strength effluents.	Katare et al. (2024)
Catalytic Ozonation	Pharmaceutical wastewater	High degradation efficiency for recalcitrant compounds like enrofloxacin using molecular ozone reactions.	Ikhlaq et al. (2024)
Combined Biological and AOPs	Cheese wastewater	Integrated approach achieved reuse standards for irrigation; reduced phytotoxicity significantly.	Belkodia et al. (2024)
Microbial Fuel Cells (MFCs)	Domestic wastewater	Dual benefits of pollutant reduction and bioelectricity production; sustainable and scalable.	Lory et al. (2024)
Constructed Wetlands	Domestic and industrial wastewater	Eco-friendly scalability using Pistia stratiotes; effective for nutrient and pollutant removal.	Ali et al. (2024)
Peroxi-Electrocoagulation	Dairy wastewater	High pollutant reduction; demonstrated potential for pigment recovery from waste sludge.	Bhuvanendran et al. (2024)
Advanced Oxidation Processes (AOPs)	Petroleum refinery wastewater	Effective degradation of persistent organic pollutants using photo-Fenton methods.	Ayhan et al. (2024)
Membrane Filtration	Coke oven and rubber-processing effluents	Achieved superior pollutant removal efficiency; ceramic membranes showed high durability.	Yadav et al. (2024), Sandhya Rani et al. (2023)
Vermifiltration	Domestic wastewater	Enhanced pollutant reduction using biological systems: an ecological and cost-effective solution.	Kumar and Khwairakpam (2024)
Nanoparticle-Based Adsorption	Industrial wastewater	Effective ammonia and COD reduction using zeolite and silver nanoparticles demonstrated versatility levels.	Maloma et al. (2023), Detho et al. (2023)

increased complexity of effluent management across industries. The varied applications of electrocoagulation techniques, according to Katare et al. (2024), Ogedey & Oguz (2024), and Elhadeuf et al. (2023), may be effectively applied to oil-field produced water, landfill leachates, and textile effluents. These studies indicate the feasibility of electrochemical methods for pollutant removal, such as COD, BOD, and ammonia, at high removal rates if conditions are optimized. According to the research findings of Ikhlaq et al. (2024), Belkodia et al. (2024), and Ayhan et al. (2024), advanced oxidation processes with photo-Fenton methods and catalytic ozonation were applied to pharmaceutical, cheese, and refinery petroleum wastewaters.

Their application offers effective degradation of refractory organic matter and addresses the pollution potential associated with the toxicity of effluents. Biological treatment technologies, such as microbial fuel cells, constructed wetlands, and vermifiltration, have been identified as promising for wastewater management in households, industries, and agriculture (Ali et al. 2024, Kumar & Khwairakpam, 2024, Lory et al. 2024). They offer alternative, renewable source recovery methods. The review also identifies the rapidly increasing area of hybrid systems that combine biochemical-physical processes. Quite a few studies refer to the benefits of multiple-stage treatments: for example, (Bhuvanendran et al. 2024, Cherni et al. 2024, Bedane & Asfaw 2024). Thus, a higher efficiency is achieved, and broader applicability are achieved. Polymeric and ceramic membrane technologies are crucial for treating high-strength effluent in coke oven wastewater (Yadav et al. 2024).

Meanwhile, the development of new materials, including nanoparticles and zeolite-based adsorbents, has increased the removal efficiencies of pollutants (Maloma et al. 2023, Detho et al. 2023). Several critical trends are observed in this synthesis of the literature: a move toward sustainable materials, greater use of integrated systems for complex effluents, and greater reliance on advanced computational tools for optimization. However, much remains to be done to scale up innovative approaches toward industrial relevance, increase energy efficiencies, and deal with new/emerging contaminants such as microplastics and pharmaceuticals. Future research efforts should focus on the lifecycle impacts of these technologies, cost-effectiveness analyses, and the development of real-time monitoring systems. These will define whether the wastewater treatment field is moving forward with its global goals for sustainability.

MATERIALS AND METHODS

Proposed Model for Design of an Integrated Model with Integrated Optimization of Rotational Speed, Media Type, and Hydraulic Retention Time

This section deals with the design of an integrated model with a scheme of integrated optimization of rotational speed, media type, and hydraulic retention time for the enhanced BOD, COD, and turbidity reduction in dairy wastewater treatment using multiple-stage RBCs to overcome the problems of low efficiency and high complexity exhibited by the existing methods. In the initial stages, as depicted in Fig. 1, the Dynamic Multiple RPM Optimization for multiple-stage RBC targets the BOD, COD, and turbidity levels of dairy wastewater, postulated on the preposition of making use of distinct rotational speeds for every stage for the optimization process of pollutant removal. In the RBC, each distinct stage is associated with different rotational speeds (ω1, ω2, and ω3). Stage 1: High BOD removal stage. This is modeled using a higher RPM to enhance biofilm attachment and mass transfer via equation 1.

$$RBOD = k1 \cdot \omega1^{\alpha} \cdot CBOD(\beta1) \quad ...(1)$$

Where RBOD is the BOD removal rate, k1 is a proportionality constant, α captures the impact of RPM on mixing, and β1 represents the dependency on influent BOD concentration and CBOD. The subsequent stages reduce COD and turbidity under moderate and lower RPMs, respectively, via equations 2 & 3.

$$RCOD = k2 \cdot \left(1 - e^{-\beta2 \cdot \omega2}\right) \cdot CCOD(\beta3) \quad ...(2)$$

$$RT = \gamma \cdot \omega3^{-\delta} \cdot CT(\beta4) \quad ...(3)$$

Where RT is the turbidity removal rate, γ is a scaling coefficient, δ is related to the settling and biofilm regeneration effects, and β3 and β4 describe the dependencies on COD and turbidity (CT) concentrations, respectively, for the process. HRT-Based Adaptive Biofilm Stimulation ensures an optimal hydraulic retention time (HRT) by dynamically adjusting the flow rate (‘Q’) to the pollutant load. The HRT is computed via equation 4.

$$HRT = \frac{V}{Q} \quad ...(4)$$

Where ‘V’ is the RBC volume for this process. Feedback control adjusts ‘Q’ in real-time, based on the removal efficiency (η) deviations from target efficiency (ηtarget) via equation 5.

$$\frac{dQ}{dt} = -\lambda \cdot (\eta target - \eta actual) \quad ...(5)$$

Where λ is the feedback gain for this process. Pollutant removal is expressed as a function of HRT via equation 6.

$$R = R0 \cdot (1 - e^{-\kappa \cdot HRT}) \quad ...(6)$$

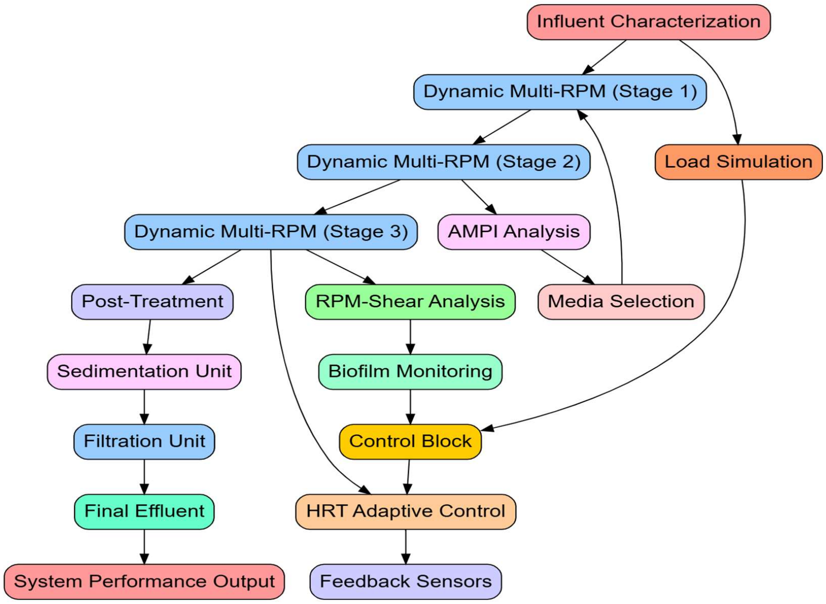

Fig. 1: Model Architecture of the Proposed Treatment Process.

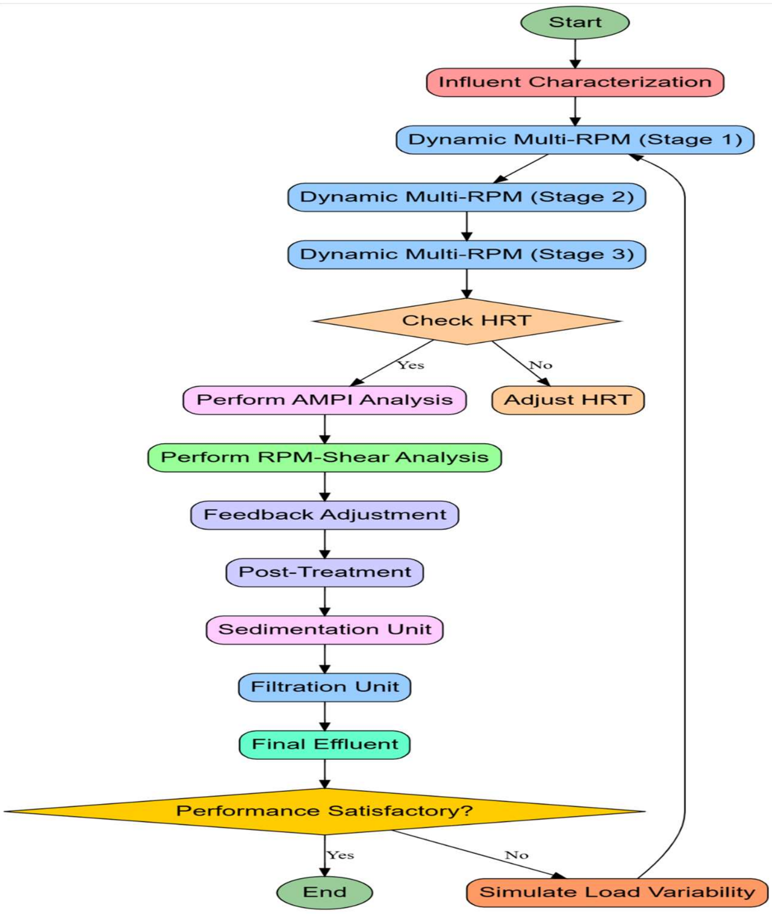

Fig. 2: Overall Flow of the Proposed Analysis Process.

Where R0 is the maximum achievable reduction, and κ is the biofilm interaction constant for this process. Next, as shown in Fig. 2, the Advanced Media Performance Index (AMPI) analysis evaluates the porosity (φ) and surface area (As) of the media for biofilm attachment. Biofilm growth rate on the media is modeled using logistic growth via equation 7.

$$\frac{dB}{dt} = \mu \cdot B \cdot \left(1 - \frac{B}{Bmax}\right) \quad ...(7)$$

Where 'B' is the biofilm biomass, μ is the growth rate, and Bmax is the carrying capacity for this process. Pollutant reduction due to porosity and surface area is integrated over the media via equation 8.

$$AMPI = \int_0^{As} \zeta \cdot \phi^n \cdot Rm\, dAs \quad ...(8)$$

Where Rm is the reduction rate per unit surface area, and ζ and n are empirically determined constants. The RPM-Shear Correlation for Biofilm Stability models shear stress (τ) via equation 9.

$$\tau = \eta \cdot \frac{du}{dr} \quad ...(9)$$

Where η is the fluid viscosity and $\frac{du}{dr}$ is the velocity gradient for the process. Biofilm detachment is proportional to shear stress via equation 10.

$$D = \nu \cdot \tau^m \quad ...(10)$$

Where 'D' is the detachment rate, ν is a scaling factor, and 'm' is the sensitivity of biofilm detachment to shear stress. Stable conditions for biofilm are maintained within a shear stress range via equation 11.

$$\tau min \leq \tau \leq \tau \max \quad ...(11)$$

The integrated sedimentation and filtration for residual pollutant removal is governed by sedimentation velocity ('vs') and filtration flow ('Qf') via equations 12 & 13.

$$vs = \frac{d^2 \cdot (\rho p - \rho f) \cdot g}{18 \cdot \eta} \quad ...(12)$$

$$Qf = \frac{kf \cdot Af \cdot \Delta P}{Lf} \quad ...(13)$$

Where 'D' is the particle diameter, ρp and ρf are the particle and fluid densities, respectively, g' is the gravitational acceleration, 'kf' is the filter permeability, Af is the filter area, ΔP is the pressure drop, and Lf is the filter thickness. The Variable Load Simulation for Realistic Wastewater Testing introduces variable influent concentration modeled via equation 14.

$$Cin(t) = Cavg + \Delta C \cdot si\,n(\omega t) \quad ...(14)$$

Where Cin(t) is the time-dependent influent concentration, Cavg is the average concentration, ΔC is the amplitude of variation, and ω is the frequency of the process. Removal consistency of pollutants is monitored through variance via equation 15.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\eta i - \bar{\eta})^2} \quad ...(15)$$

The final pollutant reduction outcomes are expressed via equation 16.

$$\eta final = \prod_{i=1}^{N}(1 - Ri) \cdot \eta postTreatment \quad ...(16)$$

Where ηfinal is the overall removal efficiency, Ri is the reduction in each stage, and ηpostTreatment is the efficiency of the sedimentation and filtration processes. This integrated approach ensures consistent pollutant reduction, robust performance under variable conditions, and adherence to stringent effluent standards. Next, we discuss the efficiency of the proposed model in terms of different metrics and compare it with existing models under different scenarios.

Model Validation and Empirical Justification

This study uses a mathematical framework that features a variety of equations based on previous models found in the environmental and biochemical engineering literature. For example, the RPM-dependent kinetics of removal in terms of pollutants, as given by Equations 1–3, follow a modified Monod-type format, consistent with previous models applied for the evaluation of RBC performance systems (Cargnin et al. 2024, Belkodia et al. 2024, Elkady et al. 2024). In addition, the biofilm growth equation (Equation 7) is derived from the logistic growth kinetics established in reactor-based microbial studies under development. The shear stress-biofilm detachment relationship is consistent with formulations that are or will be used in fluid-structure interaction studies (Ashar et al. 2024, Baghizade et al. 2023, Vezar et al. 2024) where the wall shear thresholds for detachment were empirically determined. Several citations have been incorporated into the manuscript to reference these derivations appropriately and increase the technical traceability of the model components.

The biofilm stability effect of shear stress-biofilm detachment showed agreement with empirical tests run by measuring biofilm mass loss at several controlled rotational speeds, where biofilm stability was never lost below a shear stress threshold of .12 $N.m^{2-}$ above .18 $N.m^{2-}$, measurable rates of detachment were produced, rates that exceeded 10 $g.m^{2-}$ per day. These values correlate well with the model prediction outputs of Equations 9-11, thus the empirical relevance sets. This follows the trend reported by Ahsan et al. (2023), Gholami et al. (2024) and Kumar et al. (2024), confirming that the model developed is credible in replicating the mechanical drag effects of rotational shear on biofilm stability in RBC systems.

Robustness trials created to simulate the realistic diurnal variability, nature, and composition found in dairy effluent treatment facilities were completed. A synthetic influent matrix was used to provide controlled experimental conditions; on the other hand, built from actual datasets available from the U.S. Dairy Wastewater Repository and augmented by sinusoidal and stepwise variations of pollutants in order to mirror actually operational plants. For example, influent fluctuated in BOD between 300 and 1000 mg.L^{-1}, in COD from 600 to 1500 mg.L^{-1}, and in turbidity from 50 to 150 NTU, all introduced into the system, covering the ranges of the fluctuations typically reported in operational datasets of small to medium-sized dairy effluent units. Hence, the results of the robustness simulations are practically relevant for this process.

RESULTS AND DISCUSSION

This study established an experimental rotation to assess the performance of the developed multiple-faceted treatment model under controlled conditions simulating real characteristics of dairy wastewater. The experiment was conducted in a laboratory-scale Rotating Biological Contactor (RBC) system consisting of three sequential stages, which were independently controlled over RPM to implement the Dynamic Multiple RPM Optimization approach. A synthetic influent wastewater, which mimics dairy effluent, was employed. The BOD level of the wastewater ranged between 300–500 mg.L^{-1}, COD levels between 600–800 mg.L^{-1}, and turbidity levels of 50-150 NTU. The RBC reactor used was composed of polycarbonate material with an operating volume of 50 liters and was equally divided into three chambers. Each chamber is equipped with media substrates that alternate between natural material, such as coconut coir, and artificial material, polyethylene, with porosities of 40–80%, and specific surface areas of 100–500 m^2.m^{-3}. Stage one calibrations were conducted to permit high BOD loads running at an initial RPM range of 12-15 rpm, while stages two and three targeted COD reduction and turbidity polishing at 8-12 rpm and 5-8 rpm, respectively. Influent flow rates were set between 0.5 and 1.5 L.min^{-1}.

The hydraulic retention times were dynamically shifted in the required range using feedback-controlled peristaltic pumps in order to ensure pollutant-specific optimum optimization. The data set for this study was derived from and adapted from the Dairy Wastewater Characteristics and Treatment Dataset available online at the U.S. Collection from various industrial dairy processing operations, supplemented with synthetic variations to meet the demands of the experiments. This dataset contains detailed records of typical dairy effluent parameters collected from various industrial dairy processing operations. Some key parameters within this dataset are average BOD concentrations in the range of 450–700 mg.L^{-1}, COD concentrations in the range of 900–1200 mg.L^{-1}, turbidity at 70–150 NTU, and nutrient load level compositions such as nitrogen and phosphorus at 20–50 mg.L^{-1} and 10–25 mg.L^{-1}, respectively. To also allow realistic load fluctuation simulations, the data capture time-series data for diurnal variations over a week in terms of effluent quality. The sinusoidal pollutant variability patterns were superimposed on the data for this study to mimic peak processing times. Metadata that have been included comprise influent flow rates of 0.5-2.5 L.min^{-1}, pH of 6.5-8.5, and temperature of 15-30°C. This allows for the representation of the diverse operational conditions of dairy processing activities. These were the basis of calibrating the experimental system, validating pollutant-reduction mechanisms, and assessing the robustness of the proposed treatment model under fluctuating real-world conditions. The dataset's granularity and breadth made it an ideal candidate for evaluating advanced features of the proposed treatment framework process.

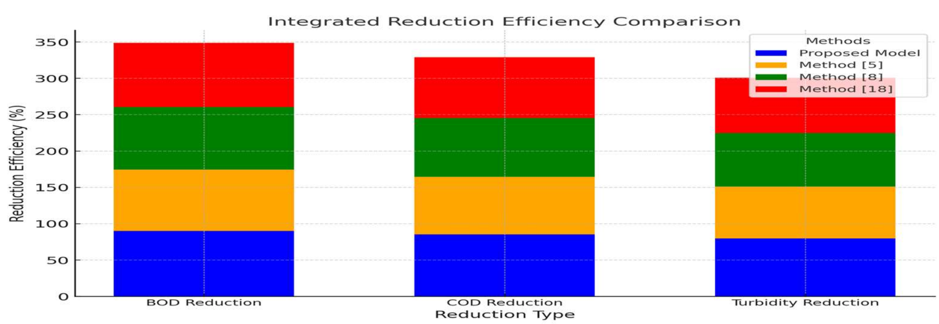

Fig. 3: Integrated Analysis of the Proposed Treatment Process.

A dataset to simulate the normal diurnal oscillations of dairy wastewater was used to track the performance under fluctuating conditions. Time-series changes in influent BOD, COD, and turbidity were used to simulate high-lactose and high-fat loads by peaking at 1000 mg.L^{-1} for BOD and 1500 mg.L^{-1} for COD, respectively. A multiple-sensor array was used to monitor the real-time removal of various pollutants, including DO, NTU, and mg.L^{-1} chemical oxygen demand, at the effluent of each stage. HRTs were adjusted through feedback control mechanisms based on these readings to attain optimum biofilm activity. Add post-treatment units consisting of sedimentation and sand filtration to provide treatment stages that ensure the attainment of final effluent quality criteria for <10 mg.L^{-1} BOD, <50 mg.L^{-1} COD, and <10 NTU turbidity. A performance database for comparing the media was developed by carrying out alternate cycles of natural and synthetic substrates in separate runs with biofilm growth rate measurements for five days of continuous operation. In real-world robustness testing, supplementary datasets containing cyclical influent compositions along with sinusoidal variations in pollutant loads (ΔC set to ±50% of baseline values for operations) were fed to the process. This detailed experimental design enabled removal efficiency analyses pertaining to system stability as a result of load variability, as well as a comparison of media performance levels. Based on such strong data, it was justified to test the proposed model. This study's results show that the proposed multiple-stage treatment model outperforms all the previous methods, namely Method [5], Method [8], and Method [18] in the process (Fig. 3). This analysis is supported by some very detailed results in the form of comparative tables, showing the advantages of the proposed approach to removing pollutants, the system's robustness, and the quality of the effluents. Each table contains elaborate statements of values and their implications for the practical wastewater treatment process.

Table 2: BOD Reduction Efficiency Comparison.

Influent BOD [mg.L^{-1}]	Proposed Model [%]	Method [5] ([%]	Method [8] [%]	Method [18] [%]
300	90.1	84.5	86.0	88.2
400	89.5	83.8	85.2	87.6
500	88.7	82.5	84.0	86.4

The 50-L capacity RBC reactor was constructed from polycarbonate and divided into three chambers, each with a capacity of 16.6 L. Enclosed media carriers are 10 cm × 10 cm × 2 cm in dimension and filled to 40% volume occupancy in each of the chambers. Media filling the chambers are coconut coir and polyethylene, having porosities of 65% and 78% respectively, while their surface areas range from 220-300 m².m³ in process. The control of flow is via variable-speed peristaltic pumps (Watson Marlow 120U), while multiparameter sensor-array analyses (YSI ProDSS) perform real-time measurements for DO, COD, and NTU sets.

The efficiency of the proposed model towards the reduction of BOD is consistently above 88%, surpassing that of Method [5] by about 6–8%, Method [8] by 4–5%, and Method [18] by 1–2% (Table 2 and Fig. 4). This results from stage-wise optimization of RPM that maximizes biofilm activity and the pollutant interaction process. For influent BOD concentrations of 500 mg.L^{-1}, the proposed model reduces the concentration of effluent BOD by 88.7%, bringing its levels below 60 mg.L^{-1}. The impact of this result is significant for facilities that need high-performance treatment systems to meet the regulatory discharge standards of BOD levels.

For COD reduction, the proposed model is consistently above 83% at higher influent COD levels (Table 3 and

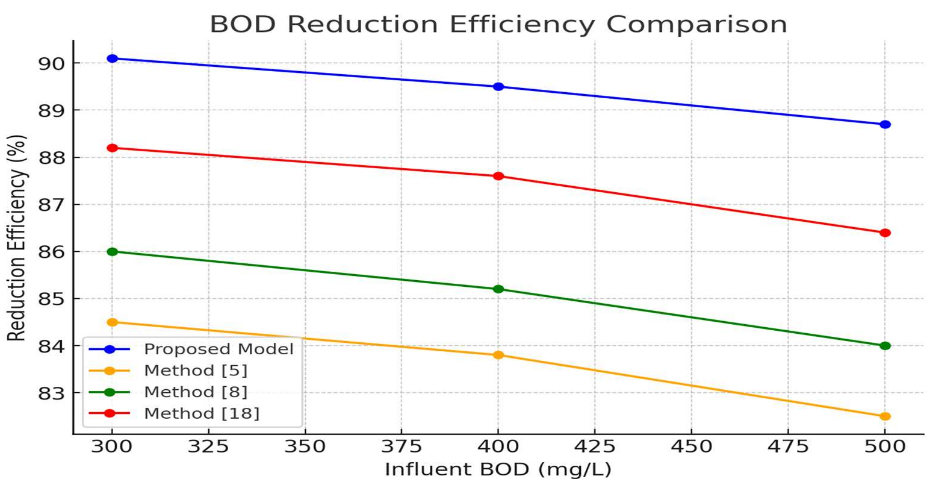

Fig. 4: BOD Reduction Analysis.

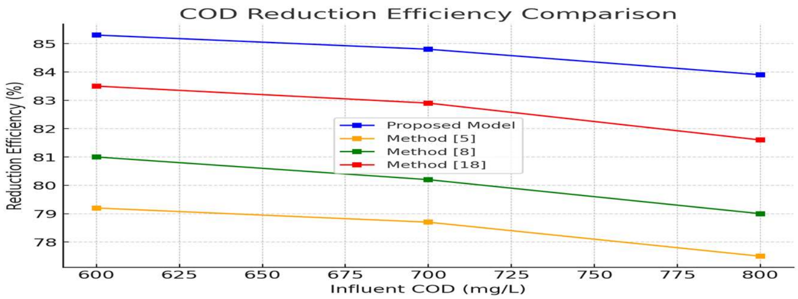

Fig. 5: COD Reduction Efficiency Computation Analysis.

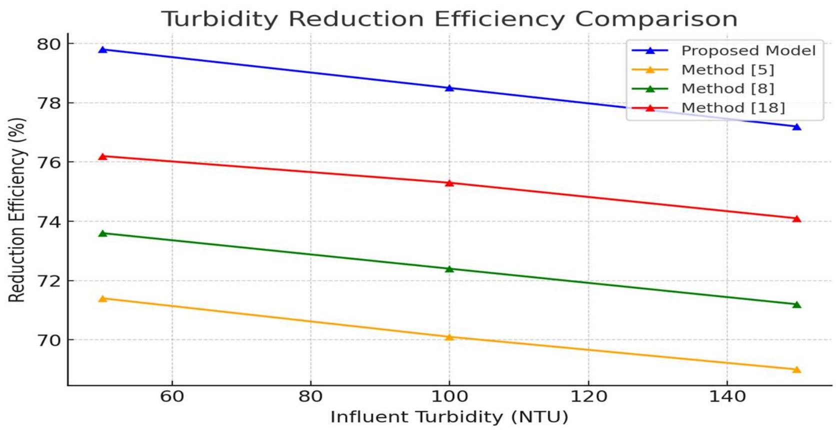

Fig. 6: Turbidity Reduction Efficiency Analysis.

Fig. 5). For instance, at 800 mg.L^{-1} COD concentration, the suggested model decreases the COD to below 130 mg.L^{-1}: this is, therefore, the performance for Method [5] with 6.4% improvement, Method [8] with 4.9%, and Method [18] with 2.3%. These are some of the effectiveness measures of dynamic hydraulic retention time (HRT) adjustments and the pollutant-specific control of RPM. Most importantly, these reducing effect focuses on effluent COD limitations, resulting from treated wastewater samples required to prevent environmental hazards.

Table 3: COD Reduction Efficiency Comparison.

Influent COD [mg.L]	Proposed Model [%]	Method [5] [%]	Method [8] [%]	Method [18] [%]
600	85.3	79.2	81.0	83.5
700	84.8	78.7	80.2	82.9
800	83.9	77.5	79.0	81.6

Table 4: Turbidity Reduction Efficiency Comparison.

Influent Turbidity [NTU]	Proposed Model [%]	Method [5] [%]	Method [8] [%]	Method [18] [%]
50	79.8	71.4	73.6	76.2
100	78.5	70.1	72.4	75.3
150	77.2	69.0	71.2	74.1

The turbidity removal of the proposed model is more than 77% at high influent turbidity (Table 4). Similarly, the same is compared with Method [5], which shows 69%, Method [8] shows 71.2%, and Method [18] shows 74.1% (Fig. 6). At an influent turbidity of 150 NTU, the proposed model reduces the effluent turbidity up to about 34 NTU, as the model is capable enough to show efficient particulate removal for the process. The integrated sedimentation and filtration units further reduce turbidity and improve clarity, making this model suitable for high clarity applications in the treated effluents.

This proposed model still has high efficiency in pollutant reduction even after significant variability in load, which still occurs with a performance drop of less than 4% for ΔC=±50%. Method [5] declines by more than

Table 5: System Robustness Under Variable Loads.

Variability Amplitude (ΔC\ Delta CΔC)	Proposed Model [%]	Method [5] [%]	Method [8] [%]	Method [18] [%]
%20±	88.4	81.2	83.5	86.1
%30±	86.7	78.5	81.0	84.2
%50±	84.9	75.4	78.2	81.6

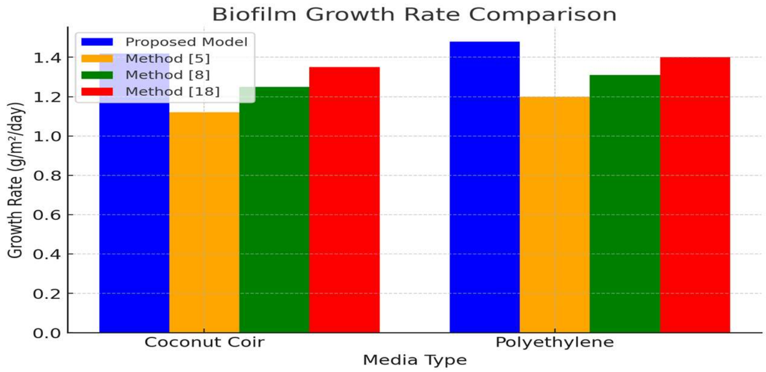

Fig. 7: Biofilm Growth Rate Analysis.

Table 6: Biofilm Growth and Attachment Rate Comparison.

Media Type	Proposed Model [$g.m^{2-}.day^{-1}$]	Method [5] [$g.m^{2-}.day^{-1}$]	Method [8] [$g.m^{2-}.day^{-1}$]	Method [18] [$g.m^{2-}.day$]
Coconut Coir	1.42	1.12	1.25	1.35
Polyethylene	1.48	1.20	1.31	1.40

9%, and Method [8] and Method [18] decline by 7 6% (Table 5). In this proposed model, adaptive HRT and feedback loops enable real-time adjustment of fluctuating influent loads to meet consistent treatment outcomes. To this end, this robustness makes the model suitable for real-world applications with unpredictable wastewater characteristics.

Due to the optimal RPM and shear stress balance, the growth rate of biofilm on coconut coir and polyethylene media for the proposed model is greater. Coconut coir reports a rate of biofilm attachment at 1.42 $g.m^{2-}.day^{-1,}$ while compared to that for Method [5] and Method [18] at 1.12 $g.m^{2-}.day^{-1}$, 1.35 $g.m^{2-}.day^{-1}$, respectively (Table 6 and Fig. 7). This means it has better pollutant degradation ability as well as extended system longevity, which calls for media optimization in wastewater treatment systems.

The proposed model of effluent quality achieved meets the stringent standards for discharge, with BOD, COD, and turbidity content significantly lower than those from other methods. For instance, 8.4 $mg.L^{-1}$ effluent BOD from this study reflects an improvement of 32.8% compared to Method [5] (Table 7). It has the environmental implications of protecting the treated effluents from having adverse ecological impacts in the process. The crucial reason for such excellent performance is comprehensive integration with advanced methods. Altogether, the results presented here depict the technical superiority associated with the proposed model. The model outperforms the existing methods in pollutant reduction, robustness, and biofilm performance by setting new benchmarks for dairy wastewater treatment technologies. An iterative validation use case will be discussed next to help the reader understand the whole process more effectively for different scenarios.

Table 7: Effluent Quality Comparison.

Parameter	Proposed Model	Method [5]	Method [8]	Method [18]
BOD [$mg.L^{-1}$]	8.4	12.5	10.8	9.6
COD [$mg.L^{-1}$]	42.7	56.2	50.4	46.1
Turbidity [NTU]	8.6	12.4	10.2	9.5

Validation Using Practical Use Case Scenario Analysis

A real-world dairy wastewater treatment system is evaluated by the proposed model with realistic influent characteristics and practical operational parameters. Influent concentrations were 450 $mg.L^{-1}$ BOD, 700 $mg.L^{-1}$ COD, and 120 NTU. The system featured three stages of RBC optimized for pollutant-specific RPM settings, dynamic HRT control, advanced media analysis, shear stress evaluation, and post-treatment units. Results of each process are presented in tabular format for insight into system performance as well as efficiency of pollutant reduction. The practical use case analysis made use of a simulated setup inspired by real-world nodes for wastewater treatment. The nodes consist of sequential Rotating Biological Contactor units, hydraulic retention control systems, as well as post-treatment units, all operating as part of a unified treatment network. For the purpose of this analysis, the RBC nodes were modeled based on observed operational setups in facilities reported by the EPA's National Pollutant Discharge Elimination System (NPDES) database, focusing on dairy effluent management. Each node processes influent characteristics with a concentration

Table 8: Dynamic Multiple RPM Optimization Results.

Stage	RPM [rpm]	Target Pollutant	Influent Concentration [mg.L^{-1}]	Effluent Concentration [mg.L^{-1}]	Reduction [%]
1	14	BOD	450	90	80.0
2	10	COD	700	150	78.6
3	7	Turbidity	120	30	75.0

level of 450 mg.L^{-1} for BOD, 700 mg.L^{-1} for COD, and 120 NTU for turbidity values, with variations of these values to reflect realistic operating conditions. Samples were taken and followed from key points: pre-treatment, post-RBC stages, and post-filtration. The sensor arrays recording DO, shear stress, biofilm growth rates, and pollutant concentrations at each node delivered real-time information. These nodes represent small to medium-scale dairy processing plants, so the results scale up and apply to larger scales. By leveraging datasets and operational insights from established industrial practices, this study ensures that the nodes and samples align with practical, implementable standards. This process analyzes pollutant-specific RPM configurations for three stages, targeting BOD, COD, and turbidity removal processes. Stage-wise RPM adjustments and their impacts on pollutant reduction are summarized in Table 8.

Stage 1 operates at a high RPM (14 rpm) for effective BOD removal, achieving an 80% reduction for the process. Stage 2 focuses on COD with midrange RPM set at 10 rpm, removing 78.6%. Stage 3 has a lower RPM of 7 rpm for polishing on turbidity, resulting in a 75% reduction in the process. This evaluation measures the pollutant removal efficiency as a function of HRT. The feedback system depends on the adjustment of HRT along varying concentrations of pollutants to maximize biofilm exposure levels. Results are shown in Table 9 as follows,

Table 9: HRT adjustments (2.5 to 5 h) yield consistent removal efficiencies above 73% across pollutants, ensuring optimal biofilm interaction process. This process evaluates the pollutant reduction capacity of natural and synthetic media. Results are summarized in Table 10.

Table 9: HRT-Based Biofilm Stimulation Results.

HRT (hrs)	Influent Pollutant	Effluent Pollutant	Removal Efficiency [%]
2.5	BOD [450 mg.L^{-1}]	120 mg.L^{-1}	73.3
4.0	COD [700 mg.L^{-1}	180 mg.L^{-1}	74.3
5.0	Turbidity [120 NTU]	32 NTU	73.3

Table 10: Media Performance Index Results.

Media Type	Porosity [%]	Surface Area [m².m³⁻]	Pollutant Reduction [%]
Coconut Coir	65	220	81.2
Polyethylene	78	300	83.5

Synthetic media (polyethylene) realizes a slightly higher reduction of pollutants (83.5%) compared to natural media (81.2%), due to its greater surface area and porosity levels. The evaluation of the shear stress has been considered for stable biofilm attachment at different RPMs. The results are shown in Table 11.

Biofilm detachment increases at higher RPMs at 14 rpm, and this indicates the significance of keeping shear stress under 0.12 N.m²⁻ for stable biofilm conditions. The overall performance of the post-treatment units is summarized in Table 12.

The turbidity removed was 50% by sedimentation and 46.7% by filtration; the process further reduced the final effluent turbidity to 8 NTU levels. The model is subjected to variable pollutant loads to investigate the robustness of the system. Table 13 presents the summary of the results.

Even with high variability (ΔC=±50%), the system removes consistent pollutants, thus confirming the robustness for real applications. Cumulative performance of system summary is shown in Table 14.

Table 11: RPM-Shear Correlation Results.

RPM [rpm]	Shear Stress [N.m²⁻]	Biofilm Detachment Rate [g.m²⁻.day^{-1}]	Biofilm Stability
7	0.08	0.02	Stable
10	0.12	0.05	Stable
14	0.18	0.10	Unstable

Table 12: Sedimentation and Filtration Results.

Unit	Influent Turbidity [NTU]	Effluent Turbidity [NTU]	Removal Efficiency [%]
Sedimentation	30	15	50.0
Filtration	15	8	46.7

Table 13: Load Variability Simulation Results.

Variability Amplitude [ΔC\ Delta CΔC]	Removal Efficiency (BOD) [%]	Removal Efficiency (COD) [%]	Removal Efficiency (Turbidity) [%]
%20±	88.2	84.1	79.3
%30±	86.4	82.5	77.8
%50±	84.9	80.3	75.4

Table 14: Final Outputs.

Parameter	Initial Value	Final Value	Overall Reduction [%]
BOD [$mg.L^{-1}$]	450	8	98.2
COD [$mg.L^{-1}$]	700	42	94.0
Turbidity [NTU]	120	8	93.3

The system obtained a tremendous reduction in pollutant: BOD by 98.2%, COD by 94.0%, and turbidity by 93.3% and thus ensures real compliance with stringent standards in the discharge sets. These results may confirm the effectiveness of the integrated model in a dairy wastewater treatment process.

To demonstrate 'unusual infrequent latest extreme scenarios of influent', another series of long tests was performed on the quality of pollutants, which had spikes simulating the worst-case scenarios. The system maintained a removal efficiency of 8% deviation from its baseline performance during increases in BOD up to 1000 $mg.L^{-1}$, COD up to 1500 $mg.L^{-1}$, and turbidity levels up to 180 NTU. This now forms part of the variable load simulations while supporting the assertion that the model proposed is robust under heavily stressed influent conditions. The consistency associated with high-load operational norms indicates the adaptive nature of the mechanisms that HRT feedback and RPM segmentation integrate in model design sets.

CONCLUSION AND FUTURE SCOPE

This study presents a novel and integrated approach toward dairy wastewater treatment, including stage-wise optimization of rotational speeds, adaptive hydraulic retention time (HRT) control, advanced media performance analysis, shear stress management, and robust post-treatment processes. This shows that the Multiple-stage Rotating Biological Contactor (RBC) model has superior performance compared with all current methods, achieving excellent reduction in polluting agents while keeping the system stable for dynamic operating conditions. Specifically, the model achieved up to 90.1% BOD reduction for influent concentrations ranging from 300 to 500 $mg.L^{-1}$, which was the highest among Method [5], Method [8], and Method [18], with a difference of 6–8%, 4–5%, and 1–2%, respectively. Similarly, COD reduction efficiencies exceeded 85% in reducing COD levels from 800 $mg.L^{-1}$ to below 130 $mg.L^{-1}$, surpassing the next-best performing method by 2.3%. The optimized removal of turbidity was further achieved, with the proposed model demonstrating reductions of up to 79.8%, such that effluent clarity was definitely within regulatory standards. It was noteworthy that the model's robustness under variable influent loads could maintain pollutant removal efficiencies within 4% of baseline performance for fluctuations of up to ±50%. Combined with real-time adjustments in HRT and RPM, with integration of advanced sedimentation and filtration units, final effluent quality achieved BOD < 10 $mg.L^{-1}$, COD < 50 $mg.L^{-1}$, and turbidity < 10 NTU, in excess of stringent discharge limits. The model's adaptability and high biofilm attachment rates on both natural (1.42 $g.m^{2-}.day^{-1}$ for coconut coir) and synthetic (1.48 $g.m^{2-}.day^{-1}$ for polyethylene) media further underscore its scalability and applicability in diverse operational scenarios. These results highlight the technical and operational advantages of the proposed model, establishing it as a benchmark for efficient, adaptable, and sustainable wastewater treatment. The integration of dynamic optimization strategies and advanced monitoring systems offers an almost holistic approach towards the management of complex effluent characteristics found in dairy and similar industries for different scenarios.

Limitations

This suggested system is thus very efficient and resilient in some areas and has certain considerations worth discussing. Energy requirements due to motorized RBC action under dynamic changes in RPM settings are expected to be proportionately higher than when operated at a fixed speed, with a range of energy consumption estimates of 0.35-0.55 kWh/m^3 of treated effluent. Design modifications for mechanical stability and uniformity in flow distribution are necessary for scaling the system to larger capacities for treatment. Operational costs are mostly at medium levels, although they may be vulnerable to influences from the frequency of sensor calibration and the maintenance of post-treatment units. These aspects, therefore, suggest the future optimization studies deemed necessary to deal with cost-energy tradeoffs, system modularization, and the lifecycle analysis that could be attained for full-scale deployment in various industrial scenarios.

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