Study on Advanced Biological Treatment for Pharma Effluents Using Bioreactor Systems

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Abstract: Pharmaceutical wastewater from a penicillin production facility was treated using Membrane Bioreactors (MBRs) and Sequencing Batch Reactors (SBRs) under two organic loading rates (OLRs). At low OLR (0.22 kg-COD/m³/day), both systems achieved regulatory compliance except for Total Dissolved Solids (TDS). MBRs showed superior solids removal, while SBRs demonstrated enhanced degradation of aromatic compounds (UVA_{524} reduction). At high OLR (2.92 kg-COD/m³/day), both reactors exhibited instability due to foaming, likely caused by inhibitory aromatics. Ozonation was evaluated as a pre-treatment for two effluent streams. It significantly improved biodegradability in the strong stream (UVA_{524} reduction, pH drop, increased BOD_5; COD) but was less effective on biofilter-treated effluent. Results highlight the efficacy of combining oxidative and biological processes for robust pharmaceutical wastewater treatment.

Keywords: *Pharmaceutical Wastewater, MBR, SBR, Ozonation, Biodegradability, Aromatic Compounds.*

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I. INTRODUCTION:

Industrial expansion has led to the release of persistent pollutants pharmaceuticals, dyes, agrochemicals, and heavy metals into aquatic ecosystems, challenging conventional treatment due to their chemical stability and toxicity. Emerging contaminants (ECs), especially pharmaceutical and personal care products (PPCPs), pose growing ecological and health risks due to their persistence and bioaccumulation potential (Wijekoon et. al., 2014; Asante-Sackey et al., 2022; Jin et al., 2022).

Anthropogenic sources such as industrial discharge, urban runoff, and agriculture contribute to elevated EC levels. Heavy metals from sectors like mining, electroplating, and energy production further intensify pollution. Conventional sorbents (e.g., bacteria, fungi, algae) show limited efficacy due to effluent complexity. A Sustainable Alternative: In this context, biological treatment technologies particularly bioreactor-based systems offer a sustainable and environmentally responsible approach to industrial wastewater management. Bioreactors utilize live microorganisms to degrade or transform toxic substances into less harmful compounds. These systems create controlled environments that support microbial growth and optimize the breakdown of pollutants, including hazardous chemicals, heavy metals, and organic matter. By leveraging biological mechanisms, bioreactors significantly reduce the reliance on chemical treatments, thereby minimizing the formation of secondary pollutants and toxic by-products (as illustrated in Fig. 1). This approach not only enhances treatment efficiency but also promotes the preservation of water quality, protection of aquatic life, and conservation of biodiversity. Moreover, bioreactor technologies align with the principles of a circular economy by enabling resource recovery from wastewater. For instance, anaerobic digestion a key bioreactor process can convert organic matter and nutrients into biofertilizers or biogas, offering sustainable alternatives to synthetic fertilizers and fossil fuels.

Extensive research supports bioreactors' efficacy in industrial wastewater treatment and their role in advancing sustainability, including Rosenfeld & Feng (2011), DeLorenzo et al. (2001), Li et. al., (2019), Mahmood et. al., (2011), Kumar (2016), Wang & Chen (2009), Mudhoo et. al., (2012), Sharma (2021), Rajput et. al., (2021), Khan (2022), and Abdelfattah et. al., (2023). Their findings underscore the transformative potential of bioreactors in revolutionizing industrial wastewater treatment and advancing global sustainability goals.

II. MATERIAL AND METHODS:

➢ *Wastewater Collection and Preparation*

Two wastewater streams strong and weak were collected from a pharmaceutical facility and stored at 4 °C in the dark to prevent degradation. A 1:2 volumetric mixture was prepared, adjusted to pH 7 using phosphoric acid, and supplemented with 0.28 g/L urea to enhance nitrogen content. This influent was used for biological treatment in Membrane

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Bioreactors (MBRs) and Sequencing Batch Reactors (SBRs). Separately, biofilter-treated effluent was collected for ozonation experiments without modification.

- *Bioreactor Setup and Operation:*

Aerobic treatment was conducted using duplicate MBRs (7 L) and SBRs (4 L). MBRs utilized flat-sheet polyolefin membranes (0.45 µm pore size, 0.11 m² surface area) operated on an 8-min suction/2-min relaxation cycle. SBRs followed a 24-hour cycle: 40 min feeding, 22.3 h reaction, 30 min settling, and 30 min withdrawal. All reactors were maintained at 25 ± 5 °C with hydraulic retention times of 7-8 days the operation is illustrated in Fig. 1.

- *Ozonation Process:*

Ozonation was performed at KBCNMU, Jalgaon, using a lab-scale generator producing ozone at 5.6 g/h from bottled oxygen (5 L/min flow rate). Batch experiments treated 150 mL samples in Drechsel bottles. Ozone dosage was quantified via iodometric titration (APHA, 2005; Trivedy & Goel, 1984), with ozone demand calculated by subtracting excess and residual ozone from the total dose. Samples were collected periodically to monitor reaction kinetics and treatment efficacy.

- *Analytical Procedures:*

Physicochemical parameters TDS, TSS, VSS were measured by centrifugation (15,000 rpm, 15 min). COD, BOD_5, and pH were analysed per APHA (2005) and Trivedy & Goel (1984). Aromatic compounds were assessed via UVA_{524}; visible absorbance at 580 nm indicated coloration. TOC and TN were measured using a Shimadzu TOC/TN analyser. Inorganic ions (NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}) were quantified via ion chromatography. Microbial analysis of foam-forming bacteria was conducted using Gram staining and bright-field microscopy (100X oil immersion).

III. RESULT AND DISCUSSION:

- *Wastewater Characterization:*

Weekly analysis of four streams strong, weak, mixed, and biofilter effluent revealed significant variability in chemical and biological profiles. The strong stream exhibited high COD and UVA_{524} values, elevated non-bioavailable nitrogen, low phosphorus, and an alkaline pH (11.3), necessitating neutralization. The weak stream had lower pollutant loads but lacked sufficient nutrients for standalone biological treatment. A 1:2 blend of strong and weak streams, supplemented with urea and phosphoric acid, achieved a balanced C:N:P ratio (100:20:5), pH 7.3, and BOD_5; COD of 0.8 optimal for microbial degradation. Biofilter effluent retained 47% of the mixed stream's COD, exhibited biomass washout (high TSS/VSS), and showed improved biodegradability (BOD_5; COD = 0.9).

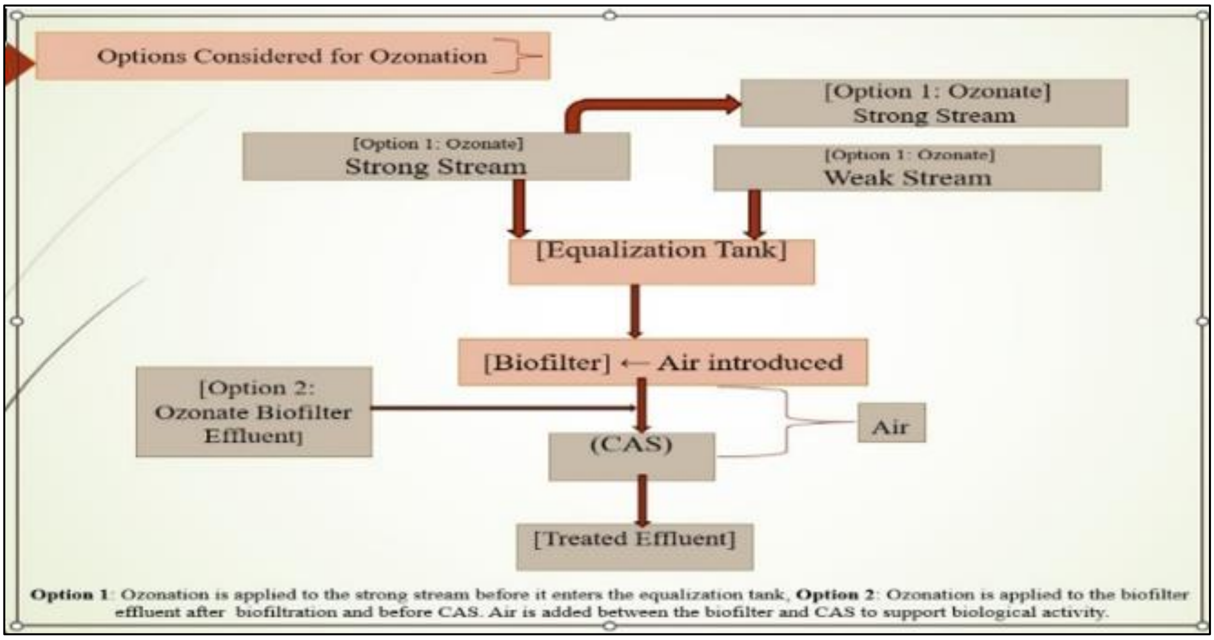

Fig 1 Depicts the Treatment Process Currently in use by the Pharmaceutical Company for Managing its Wastewater, as well as the Ozonation Options Explored in this Research.

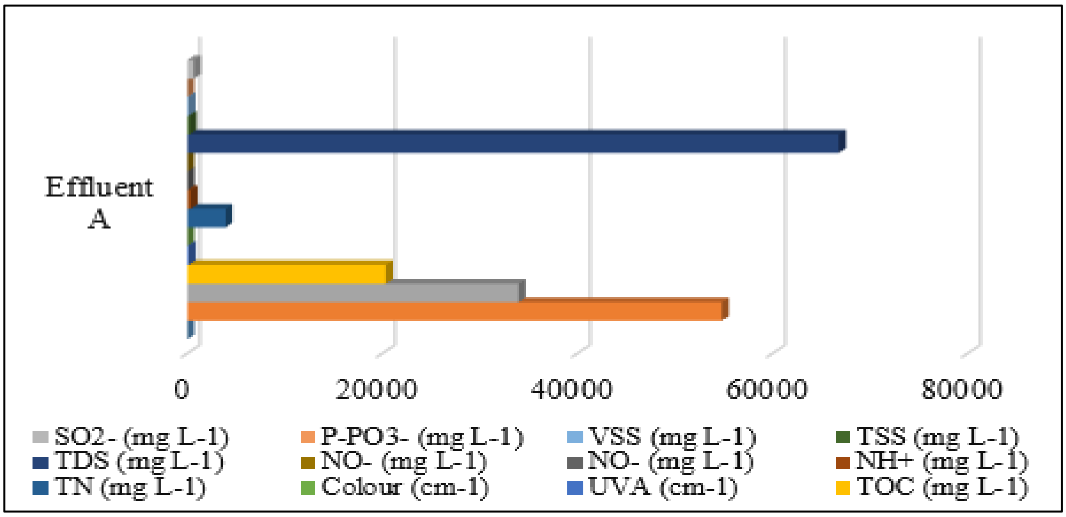

Fig 2 Characteristics of Pharmaceutical Wastewater, of the (Effluent A) Strong Stream Sample.

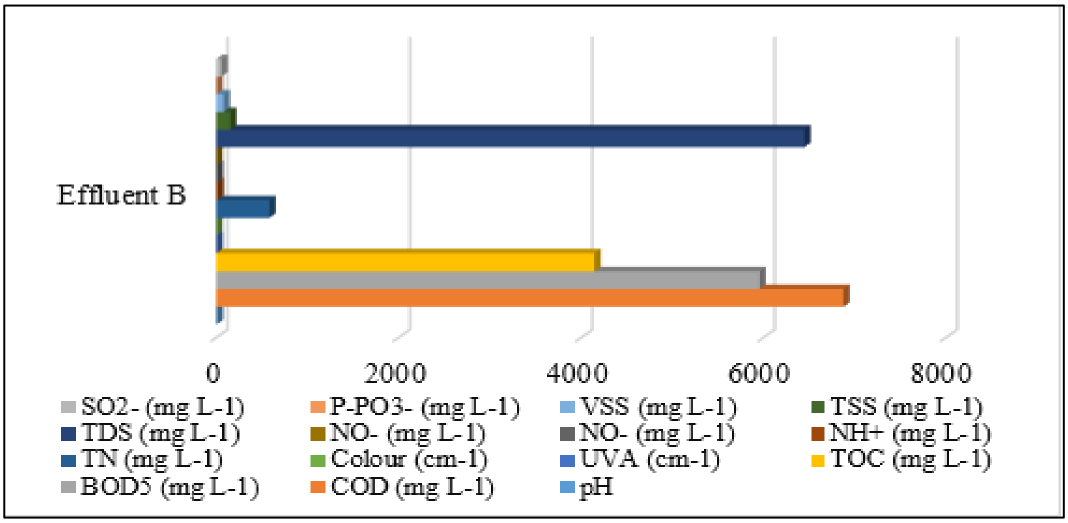

Fig 3 Summarizes the Pharmaceutical Wastewater Profile for the (Effluent B) Weak Stream Sample.

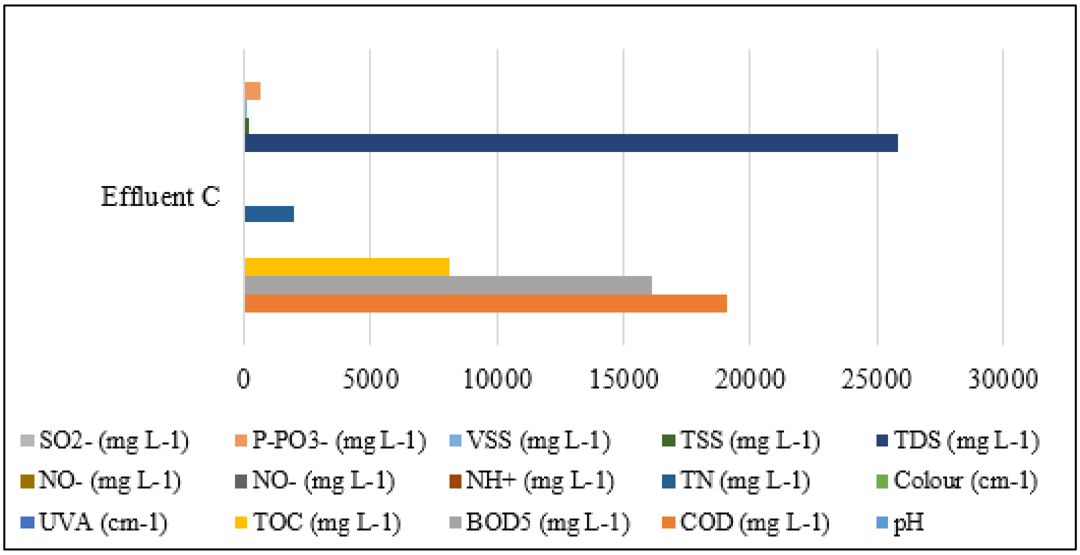

Fig 4 Characteristics of Pharmaceutical Wastewater, of the (Effluent C) Mixed Stream Sample.

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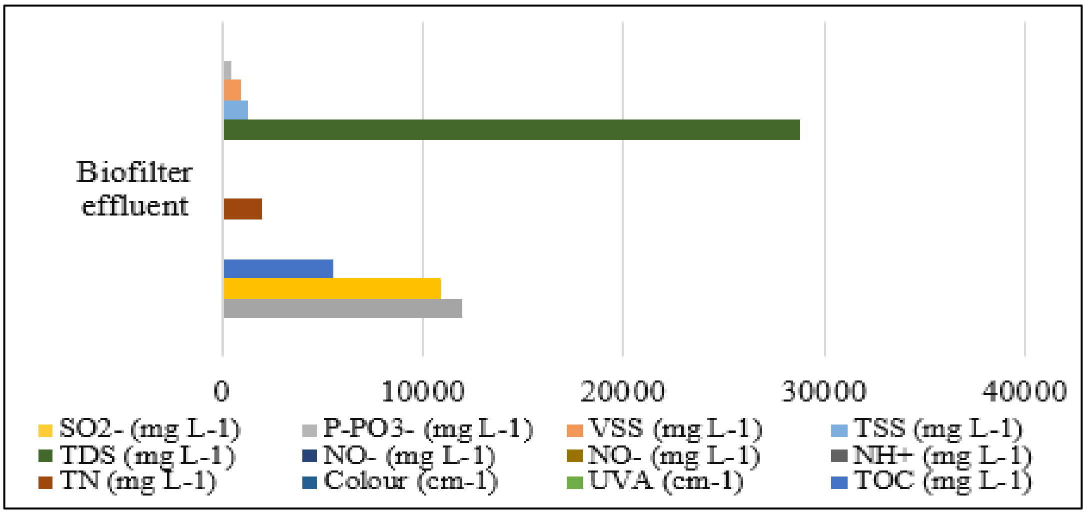

Fig 5 Summarizes the Pharmaceutical Wastewater Profile for the (Biofilter Effluent) Sample.

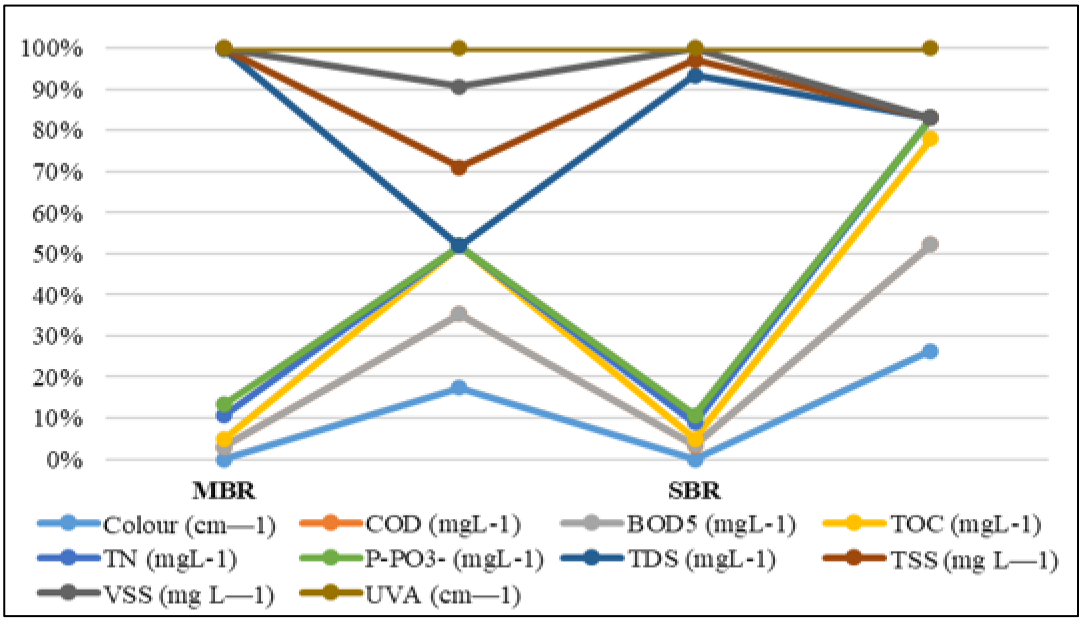

Fig 6 Performance Comparison of MBR and SBR in Pharmaceutical Wastewater Treatment

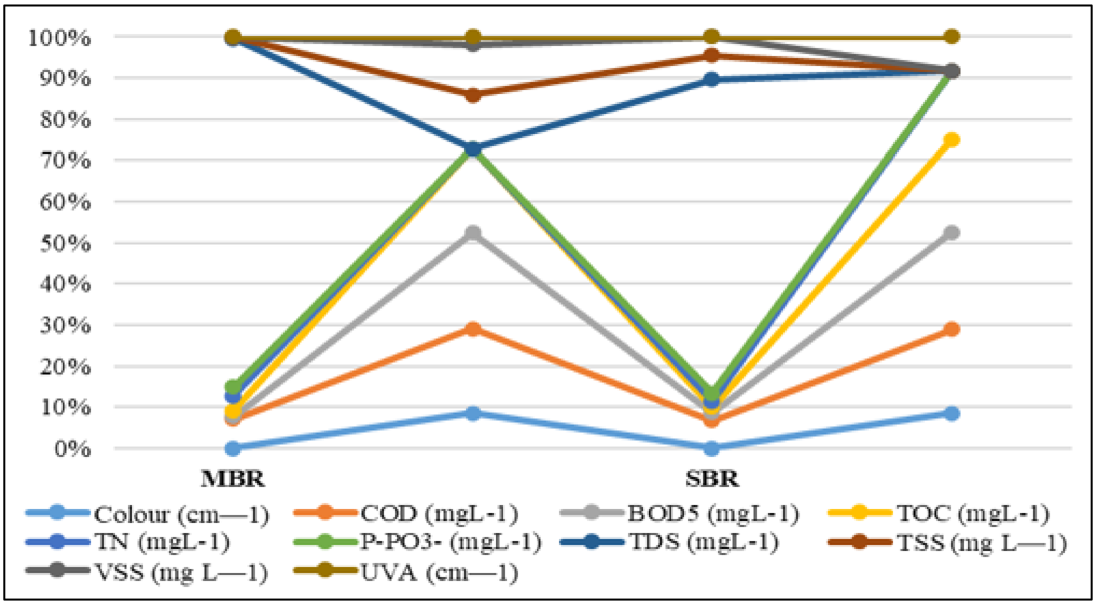

Fig 7 Treatment Efficiency of MBR and SBR at Different Organic Loading Rates

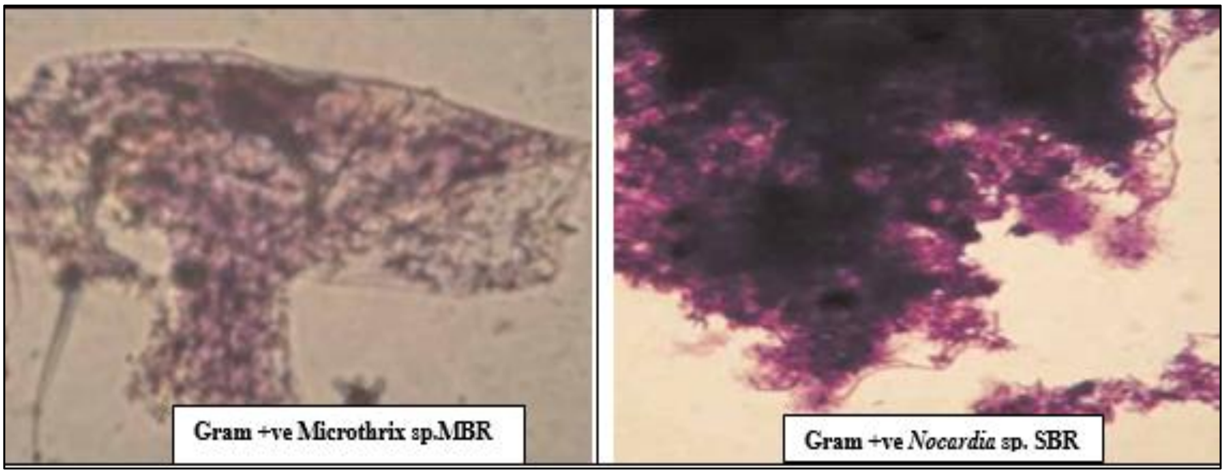

Fig 8 Shows with Thin, Smooth Curves in the MBR Foam, and Nocardia Sp. with Short, Branched Filaments in the SBR Foam.

- *Ozonation:*

Ozonation was applied to the strong stream and biofilter effluent to enhance biodegradability. Significant reductions in UVA_{524} and pH were observed, indicating effective breakdown of aromatic compounds. (refer to Fig. 2 to 5). Optimal ozone demand for the strong stream was 0.5 g/g-COD, consistent with prior studies on melanoidin-rich wastewater (Santo et. al., 2013; Thangaraj et. al., 2021; Liu et. al., 2018; Lellis et. al., 2019). While COD remained stable, BOD_5 increased, improving the BOD_5:COD ratio from 0.64 to 0.89. In contrast, ozonation of biofilter effluent yielded modest improvements due to lower initial aromatic content, confirming that ozonation is most effective when applied to untreated high-strength streams.

- *Biological Treatment Performance:*

MBRs and SBRs were evaluated under low (0.22 ± 0.03 kg-COD/m³/day) and high (2.92 ± 0.44 kg-COD/m³/day) OLRs over three months. At low OLR, MBRs excelled in TSS/VSS removal due to membrane filtration, while SBRs achieved higher removal of dissolved organics (TOC 91%, COD 92%, BOD_5 >99%) and greater UVA_{524} reduction (60% vs. 46% in MBRs). Colour removal was also superior in SBRs (93 ± 7%). These results align with previous findings (Khan et al., 2007; Ibrahim et al., 2019).

Biomass stabilization occurred after ~42 days, with MLVSS at 1,200 mg/L (MBRs) and 600 mg/L (SBRs). Biomass yields were low (0.1–0.2 g-VSS/g-BOD_5), likely due to antibiotic inhibition and endogenous respiration. At high OLR, MLVSS rose sharply (MBRs: 14,450 mg/L; SBRs: 10,000 mg/L), and biomass yields increased to ~0.3 g-VSS/g-BOD_5. Despite high removal efficiencies (TOC ~90%, COD ~87%, BOD_5 ~98%), effluent failed discharge standards due to non-biodegradable accumulation (Fig. 6 and 7). Operational issues such as foaming and biomass loss emerged after day 120, with foam-forming bacteria (Nocardia, Microthrix) identified microscopically (Fig. 8). Nonetheless, core reactor functions remained stable, demonstrating resilience under stress. These findings corroborate studies by Chaturvedi et. al. (2021) and Zhou et. al. (2023).

IV. CONCLUSION:

Industrial expansion has intensified aquatic pollution with persistent contaminants such as pharmaceutical residues, agrochemicals, and synthetic dyes challenging conventional treatment systems. This study evaluated Membrane Bioreactors (MBRs) and Sequencing Batch Reactors (SBRs) for pharmaceutical wastewater remediation. MBRs excelled in suspended solids removal due to membrane filtration, while SBRs showed superior degradation of aromatic compounds under low organic loading, indicated by greater UVA_{524} reduction. At high organic loading rates, both systems faced operational instability, including foaming and reduced treatment efficiency, likely due to inhibitory aromatic accumulation. Ozonation, applied as a pre-treatment to the strong influent stream, significantly enhanced biodegradability (BOD_5:COD improvement), facilitating more effective biological processing.

The findings support integrated treatment strategies combining oxidative and biological processes. Future optimization should focus on continuous ozonation, targeted TDS removal, and refined nutrient dosing to improve system resilience and environmental sustainability.

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