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# Optimized Lamella Separator Pretreatment for Reducing Organic and Suspended Pollutant Loads to Enhance Ultrafiltration Membrane Performance in Industrial Wastewater Treatment

**Misda Fauici[1], Mahatma Lanuru[2], Anwar Daud[3], Eymal Bahsar Demmalino[1†]**

[1] Environmental Science Study Program, The Graduate School, Hasanuddin University, Makassar 90245, Indonesia

[2] Department of Marine Science, Hasanuddin University, Makassar 90245, Indonesia

[3] Environmental Health Department, Faculty of Public Health, Hasanuddin University, Makassar 90245, Indonesia

† Corresponding author: Eymal Bahsar Demmalino; demmallino2019@gmail.com

**Abstract:** This study evaluated the performance of an optimized lamella separator as a pretreatment unit to reduce organic and suspended pollutant loads and improve ultrafiltration membrane performance in industrial laboratory wastewater treatment. The integrated system combined lamella sedimentation and membrane filtration to enhance contaminant removal efficiency while minimizing membrane fouling. Wastewater samples were analyzed for pH, turbidity, total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metals (Cu, Pb, and Hg). The lamella separator demonstrated high effectiveness in reducing suspended pollutants, achieving removal efficiencies of 80% for turbidity and 75% for TSS. However, removal of dissolved organic pollutants was relatively limited, with COD and BOD reductions of approximately 30% and 25%, respectively. Subsequent ultrafiltration significantly improved treatment performance, resulting in cumulative removal efficiencies of 98.8% for TSS, 98% for turbidity, 79% for COD, and 85% for BOD. Heavy metal concentrations were also substantially reduced, with Cu, Pb, and Hg removal efficiencies reaching approximately 95%, producing permeate that complied with environmental discharge standards. Membrane performance analysis showed an initial flux of 100 L $m^{-2}$ $h^{-1}$, which decreased by approximately 35% after 8 h of continuous operation due to reversible cake-layer fouling. Periodic backwashing successfully restored membrane flux to approximately 90% of its initial value. Operational optimization indicated that a hydraulic retention time of 60 min in the lamella separator and an operating pressure of 2 bar provided the most stable and efficient system performance. The results confirm that lamella separator pretreatment effectively decreases pollutant loading to the ultrafiltration membrane, thereby improving membrane stability and extending operational lifespan. This integrated system offers a sustainable and efficient alternative for industrial wastewater treatment with lower secondary waste generation compared with conventional adsorption- or chemical-based methods. Future studies are recommended to investigate long-term pilot-scale performance, economic feasibility, membrane lifespan under continuous operation, and integration with advanced cleaning or hybrid treatment technologies to further improve process sustainability and fouling control.

**Keywords:** lamella separator; ultrafiltration membrane; Industrial wastewater; Membrane fouling; Suspended solids removal; Wastewater treatment efficiency

## 1. INTRODUCTION

Industrial wastewater generated from laboratory and chemical processing activities contains complex mixtures of suspended solids, dissolved organic compounds, and hazardous heavy metals that can seriously threaten aquatic ecosystems and public health if discharged without proper treatment. Parameters such as turbidity, total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), and toxic metals including copper (Cu), lead (Pb), and mercury (Hg) are commonly used to evaluate the pollution level of industrial effluents. High concentrations of these contaminants contribute to oxygen depletion, bioaccumulation, ecological toxicity, and long-term environmental degradation (Kakahi et al., 2011; Kalshan et al., 2025; Koju et al., 2022; Kumari, 2010; Lemessa et al., 2023; Phiri et al., 2005; Sa'adah et al., 2025). Conventional wastewater treatment systems are often unable to efficiently remove both particulate and dissolved pollutants simultaneously, particularly under fluctuating wastewater characteristics. Increasingly stringent environmental regulations have therefore encouraged the development of integrated and more sustainable treatment technologies capable of improving pollutant removal efficiency while minimizing operational limitations.

Among the available treatment technologies, lamella separator systems have attracted attention because of their ability to enhance solid–liquid separation using inclined plate sedimentation. Previous studies reported that lamella separators effectively reduce suspended particles and turbidity in industrial wastewater with relatively low energy consumption and compact operational design (Bach & Schoenbrunn, 2022; Tiwari et al., 2025). The system increases sedimentation efficiency by enlarging the effective settling area and shortening particle settling distance. However, although lamella separators are highly efficient for removing suspended contaminants, their performance in eliminating dissolved organic pollutants and dissolved heavy metals remains limited. Several studies demonstrated that sedimentation-based systems alone are insufficient to achieve complete compliance with wastewater discharge standards for COD, BOD, and dissolved contaminants (Abbas et al., 2024; Kriech & Osborn, 2022; Zhang et al., 2025). Consequently, additional advanced treatment processes are required to improve overall effluent quality.

Membrane filtration technologies, particularly ultrafiltration membranes, have been widely investigated as advanced wastewater treatment methods because of their high capability in removing fine particles, microorganisms, colloids, and certain dissolved contaminants. Studies by (Mohammed et al., 2024) and (Li et al., 2023) reported that membrane filtration significantly improves effluent quality and achieves high removal efficiencies for organic pollutants and heavy metals. Nevertheless, membrane fouling remains one of the major operational challenges limiting long-term membrane performance and increasing maintenance costs. Fouling caused by suspended solids, organic matter accumulation, and cake layer formation reduces membrane flux and shortens membrane lifespan. Previous approaches such as adsorption using activated carbon or chemical coagulation have been proposed to minimize membrane fouling, but these methods often generate secondary waste, require chemical regeneration, or increase operational complexity (El Batouti et al., 2022; Qalyoubi et al., 2021; Skouteris et al., 2015; Wang et al., 2020). Therefore, pretreatment systems capable of reducing pollutant loading before membrane filtration are essential for improving membrane stability and operational sustainability.

The integration of lamella separator pretreatment with ultrafiltration membrane systems has emerged as a promising alternative for improving wastewater treatment efficiency and mitigating membrane fouling. Pretreatment using lamella separation can substantially decrease suspended solids and particulate organic matter before entering the membrane unit, thereby reducing fouling intensity and maintaining membrane permeability. (Bedru et al., 2025; Salem et al., 2025) demonstrated that combined gravity separation and membrane filtration systems achieved better operational stability compared with standalone membrane treatment. However, most previous studies focused primarily on pollutant removal efficiency, while limited attention has been given to the optimization of pretreatment performance and its direct role in extending membrane operational lifespan through fouling reduction. In addition, quantitative evaluations of flux recovery, hydraulic retention time optimization, and cumulative pollutant removal under integrated systems are still relatively limited, particularly for laboratory and industrial wastewater containing mixed organic and inorganic contaminants.

Based on these considerations, this study investigates the performance of an optimized lamella separator as a pretreatment unit for reducing organic and suspended pollutant loads prior to ultrafiltration membrane treatment of industrial laboratory wastewater. The significance of this study lies in its integrated evaluation of contaminant removal efficiency, membrane fouling behaviour, flux recovery performance, and operational optimization under combined treatment conditions. Unlike previous studies that focused on single-treatment approaches or pollutant removal only, this research emphasizes the synergistic relationship between pretreatment optimization and membrane performance improvement. The main research gap addressed in this study is the limited understanding of how optimized lamella separator operation contributes to fouling mitigation and membrane lifespan enhancement in integrated wastewater treatment systems. Therefore, the aim of this study is to evaluate the effectiveness of the combined lamella separator–ultrafiltration system in improving wastewater quality, reducing membrane fouling, and enhancing the operational sustainability of industrial wastewater treatment processes.

## 2. MATERIALS AND METHODS

This study was conducted to evaluate the effectiveness of an integrated lamella separator and ultrafiltration membrane system for treating industrial laboratory wastewater containing suspended solids, organic pollutants, and heavy metals. the experimental approach was designed to investigate the role of lamella separator pretreatment in reducing pollutant loading prior to membrane filtration, thereby improving membrane performance and minimizing fouling formation during operation. several operational parameters, including hydraulic retention time and membrane operating pressure, were optimized to identify the most effective treatment conditions. system performance was assessed based on pollutant removal efficiency, permeate quality, membrane flux behavior, and fouling recovery characteristics. water quality analyses were carried out before and after each treatment stage to determine the contribution of individual treatment units as well as the overall efficiency of the integrated system.

### 2.1 Study Design

To assess the specific contribution of lamella separator pretreatment to membrane performance, a membrane-only control experiment was included in the experimental design. In the control configuration, the raw industrial laboratory wastewater was directly fed into the ultrafiltration membrane system without prior lamella sedimentation. The membrane-only control was operated under the same selected ultrafiltration conditions as the integrated system, including the same membrane module, effective membrane area, filtration mode, operating pressure, feed volume, filtration duration, and cleaning procedure. The performance of the membrane-only configuration was compared with that of the integrated lamella separator–ultrafiltration system in terms of pollutant removal efficiency, initial permeate flux, flux decline during continuous operation, and flux recovery after hydraulic backwashing. This comparative design was used to determine whether lamella pretreatment provided a measurable benefit in reducing particulate loading and mitigating membrane fouling.

### 2.2 Wastewater Sampling and Characteristics

Wastewater samples were collected from chemical and biochemical laboratory activities generating mixed organic pollutants, suspended solids, and trace heavy metals. A total of three sampling events were conducted during the experimental period, and approximately 90 L of wastewater was collected for the experimental analysis. Sampling was conducted using clean polyethylene containers that had been thoroughly washed before use. For general physicochemical analyses, the containers were rinsed with the wastewater sample before final collection, whereas separate acid-washed containers were used for samples intended for heavy-metal analysis. The collected wastewater was transported to the laboratory immediately after sampling and stored at approximately 4 °C prior to analysis. Samples for turbidity, TSS, COD, and BOD analyses were analyzed within the recommended holding periods for the respective analytical methods. Samples intended for heavy-metal analysis were preserved by acidification with concentrated nitric acid to $pH < 2$ and stored at approximately 4 °C until analysis.

Before characterization and treatment experiments, the collected wastewater was thoroughly homogenized to minimize variation in the distribution of suspended and dissolved pollutants. The initial wastewater characteristics were determined for pH, turbidity, total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metals, including copper (Cu), lead (Pb), and mercury (Hg). Each analytical parameter was measured in triplicate, and the reported concentrations represent the mean values of the replicate measurements. The treatment experiments were conducted using three independent experimental runs under each operating condition, including the evaluated hydraulic retention times of 30 and 60 min and membrane operating pressures of 1, 2, and 3 bar.

Quality assurance and quality control (QA/QC) procedures were implemented throughout the sampling, preservation, sample preparation, and analytical stages. Sampling containers and laboratory glassware were thoroughly cleaned before use, and all analytical instruments were calibrated according to the manufacturer's instructions and applicable standard analytical procedures. Method blanks and calibration checks were used, where applicable, to monitor potential contamination and analytical stability. Turbidity and pH measurements were conducted using calibrated instruments. TSS was determined gravimetrically using pre-dried and pre-weighed filtration materials, followed by drying and weighing under controlled laboratory conditions. COD and BOD analyses were performed using standard wastewater analytical procedures with appropriate reagent blanks and quality-control checks. For heavy-metal determination by atomic absorption spectrophotometry (AAS), calibration curves were prepared using appropriate standard solutions, and blank measurements and calibration verification checks were performed to confirm instrument performance. Replicate measurements were conducted to evaluate analytical precision. These QA/QC procedures were applied to improve the reliability, reproducibility, and validity of the reported water-quality and treatment-performance results.

Heavy-metal concentrations were determined for copper (Cu), lead (Pb), and mercury (Hg) using atomic absorption spectrophotometry (AAS). The analytical detection limits and quantification limits of the AAS method were recorded for each target metal and considered when interpreting the measured concentrations. Because the present study did not include separate fractionation or speciation analyses, the measured metal concentrations are reported as total recoverable concentrations rather than as specifically dissolved, particulate-bound, or organically complexed species. Accordingly, the observed reduction in metal concentrations cannot be attributed exclusively to direct rejection of free dissolved metal ions by the ultrafiltration membrane. Instead, metal removal was interpreted as potentially resulting from the combined removal of particulate-associated metals, metal-containing colloids, and metal–organic complexes retained during lamella sedimentation and ultrafiltration. Any metal fraction present as truly dissolved and uncomplexed ions would be expected to pass through a conventional ultrafiltration membrane to a substantial extent. Therefore, the metal-removal results are interpreted cautiously in relation to the overall reduction in measured total metal concentrations.

## 2.3 Experimental Setup

For the membrane-only control experiment, raw wastewater was introduced directly into the ultrafiltration membrane system without passing through the lamella separator. The membrane-only configuration was operated under conditions identical to those applied to the integrated treatment system, particularly at the selected operating pressure of 2 bar and for a continuous filtration period of up to 8 h. The same membrane module, membrane area, feed volume, filtration mode, and hydraulic backwashing procedure were used for both configurations. This approach enabled a direct comparison of membrane performance under pretreated and non-pretreated feed conditions while minimizing the influence of other operational variables.

### Lamella Separator Unit

The pretreatment process was conducted using a laboratory-scale lamella separator constructed from transparent acrylic material. The separator had internal dimensions of approximately 60 cm × 30 cm × 50 cm (length × width × height), providing a total geometric volume of approximately 90 L and an estimated effective working volume of approximately 75 L after accounting for the space occupied by the inclined plates and the sludge-collection zone. The unit was equipped with 10 inclined plates, each installed at an inclination angle of approximately 60° relative to the horizontal plane. Each plate had dimensions of approximately 40 cm × 25 cm, resulting in a total effective projected settling area of approximately 1.0 $m^2$. The inclined plates increased the effective settling area within the compact reactor volume and reduced the vertical settling distance, thereby enhancing the gravitational separation of suspended particles.

Wastewater was introduced into the lamella separator at controlled flow rates of approximately 150 and 75 L $h^{-1}$ to achieve hydraulic retention times (HRTs) of 30 and 60 min, respectively, based on the effective working volume of approximately 75 L. Each experimental run used a feed volume of approximately 75 L. The HRT was determined based on the relationship HRT = V/Q, where V is the effective working volume of the separator and Q is the wastewater flow rate. During operation, the influent was introduced through the inlet section and distributed across the settling zone to promote relatively uniform hydraulic flow through the inclined plate channels. Suspended solids settled onto the inclined plates and subsequently migrated downward by gravity into the sludge-collection zone at the bottom of the separator. The accumulated sludge was removed manually and intermittently through a bottom drainage outlet at the end of each experimental run to prevent excessive sludge accumulation and minimize disturbance of the settling process. The clarified effluent was collected from the upper outlet of the lamella separator and subsequently transferred to the ultrafiltration membrane unit for further treatment.

### Ultrafiltration Membrane System

The effluent from the lamella separator was subsequently treated using a pressure-driven ultrafiltration (UF) membrane system. The membrane module was equipped with a polymeric ultrafiltration membrane, assumed to be composed of polyethersulfone (PES), with a nominal molecular weight cut-off (MWCO) of approximately 10–100 kDa and a nominal pore size in the ultrafiltration range of approximately 0.01–0.1 µm. The effective membrane filtration area was approximately 0.05 $m^2$. The membrane system consisted of a feed tank with a working volume of approximately 10 L, a pressure pump, pressure-control components, a membrane module, a permeate collection tank, and a retentate outlet. Filtration was conducted in cross-flow mode under transmembrane pressures (TMPs) of 1, 2, and 3 bar. The permeate flux was monitored throughout the filtration period, and continuous filtration experiments were conducted for up to 8 h under the selected operating conditions. The membrane was operated at ambient laboratory temperature, approximately 25 ± 2 °C.

Before each experimental run, the membrane was thoroughly rinsed with deionized water to remove residual storage solution and loosely attached contaminants and to establish consistent initial operating conditions. The membrane was then conditioned with the pretreated wastewater prior to data collection. During operation, membrane performance was evaluated by periodically monitoring permeate volume and calculating the corresponding permeate flux. The initial permeate flux under the selected operating conditions was approximately 100 L $m^{-2}$ $h^{-1}$. Physical cleaning was performed by hydraulic backwashing using clean water for approximately 5 min at the end of the filtration period or when a substantial flux decline was observed. Following backwashing, the membrane was returned to filtration mode and the recovered flux was measured to evaluate the reversibility of fouling. The flux recovery was calculated by comparing the post-cleaning flux with the initial membrane flux. Chemical cleaning was not applied during the experimental runs in order to evaluate the effectiveness of physical backwashing in controlling predominantly reversible fouling. Under the selected operating condition, the membrane flux decreased from approximately 100 to 65 L $m^{-2}$ $h^{-1}$ after 8 h of continuous filtration and recovered to approximately 90 L $m^{-2}$ $h^{-1}$ after hydraulic backwashing.

### Water Quality Analysis

Water quality analyses were conducted before treatment (influent), after lamella separation, and after ultrafiltration membrane filtration (permeate). The analyzed parameters included: pH, Turbidity, Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and Heavy metals (Cu, Pb, and Hg).

The pH was measured using a calibrated digital pH meter, while turbidity was determined using a turbidimeter. TSS measurements were performed gravimetrically according to standard filtration procedures. COD and BOD analyses were conducted following standard methods for wastewater examination. Heavy metal concentrations were analyzed using Atomic Absorption Spectrophotometry (AAS). All analytical procedures followed applicable Indonesian National Standards (SNI) and standard wastewater analysis protocols.

### Membrane Fouling and Flux Evaluation

Membrane performance was evaluated by monitoring permeate flux throughout the filtration process. Initial membrane flux was measured at the beginning of filtration and subsequently recorded periodically during operation. Flux decline was used as an indicator of membrane fouling development. Membrane flux was calculated using the following equation:

$$J = \frac{V}{A \times t} \quad (1)$$

where:

$J$ = membrane flux (L m$^{-2}$ h$^{-1}$)

$V$ = permeate volume (L)

$A$ = effective membrane area (m$^2$)

$t$ = filtration time (h)

Flux recovery after physical cleaning was evaluated to assess the reversibility of membrane fouling. During the filtration experiment, hydraulic backwashing was conducted using clean water for approximately 5 min after the continuous filtration period or when a substantial decline in permeate flux was observed. The backwashing procedure was performed by temporarily interrupting the feed and permeate flow and introducing clean water through the permeate side in the reverse direction of normal filtration to dislodge loosely attached particles and remove the accumulated cake layer from the membrane surface. After cleaning, the membrane was returned to the filtration mode, and the permeate flux was measured under the same operating conditions used for the initial flux measurement. The flux recovery ratio (FRR) was calculated as the ratio between the post-cleaning flux and the initial membrane flux, expressed as a percentage:

$$\mathrm{FRR}(\%) = \left(\frac{J_{\text{after cleaning}}}{J_{\text{initial}}}\right) \times 100 \quad (2)$$

Where $J_{\text{after cleaning}}$ is the permeate flux measured after hydraulic backwashing, and $J_{\text{initial}}$is the initial permeate flux measured before filtration. Under the selected operating condition, the initial membrane flux was approximately 100 Lm$^{-2}$ h$^{-1}$, while the flux after physical cleaning was approximately 90 Lm$^{-2}$ h$^{-1}$, corresponding to a flux recovery ratio of approximately 90%. This parameter was used to evaluate the reversibility of fouling and the effectiveness of the applied physical cleaning procedure. The high flux recovery indicated that a substantial proportion of the accumulated fouling was reversible and could be removed through hydraulic backwashing.

**Pollutant Removal Efficiency**

The efficiency of pollutant removal at each treatment stage was calculated based on the difference between influent and effluent concentrations using the following equation:

$$\text{Removal Efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (3)$$

Where:

$C_{in}$ = influent concentration

$C_{out}$ = effluent concentration after treatment

The removal efficiencies of the lamella separator, ultrafiltration membrane, and integrated treatment system were evaluated separately and cumulatively.

## 2.4 Operational Parameter Optimization

Operational parameter optimization was conducted to identify the most effective treatment conditions for achieving high pollutant removal efficiency while maintaining stable membrane performance. The evaluated parameters included hydraulic retention time (HRT) in the lamella separator and operating pressure in the ultrafiltration membrane system. Two HRT conditions, namely 30 and 60 min, were tested to evaluate their influence on suspended solid removal and pretreatment efficiency. Membrane filtration experiments were performed under operating pressures of 1, 2, and 3 bar to determine the effect of pressure on permeate flux and contaminant removal performance. In addition, membrane flux decline during continuous operation was monitored to assess fouling development, while flux recovery after periodic backwashing was evaluated to determine the reversibility of membrane fouling and cleaning effectiveness. The optimum operational condition was determined based on the highest pollutant removal efficiency, stable membrane flux, reduced fouling intensity, and effective flux recovery after cleaning procedures.

## 2.5 Data Analysis

Experimental data were analyzed using descriptive and quantitative approaches to evaluate the treatment performance of each processing stage and the overall integrated system. Average values, standard deviations, and percentage removal efficiencies were calculated for all measured parameters, including pH, turbidity, Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and heavy metals (Cu, Pb, and Hg). Removal efficiency was determined by comparing influent and effluent concentrations using the standard removal efficiency equation. Comparative analyses were conducted between the influent, lamella separator effluent, and ultrafiltration permeate to determine the individual contribution of each treatment unit to pollutant reduction and water quality improvement.

For regulatory comparison, the treated wastewater quality was assessed against the applicable Indonesian wastewater quality standards established within the regulatory framework of Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning Environmental Protection and Management. Because PP No. 22/2021 does not establish a single wastewater category specifically designated as “industrial laboratory wastewater,” the regulatory comparison in this study is presented as a benchmark comparison rather than as a direct determination of regulatory compliance for all laboratory wastewater. The applicable discharge limits for an actual laboratory facility should be determined according to the specific business or activity classification, environmental approval, and technical approval applicable to the facility.

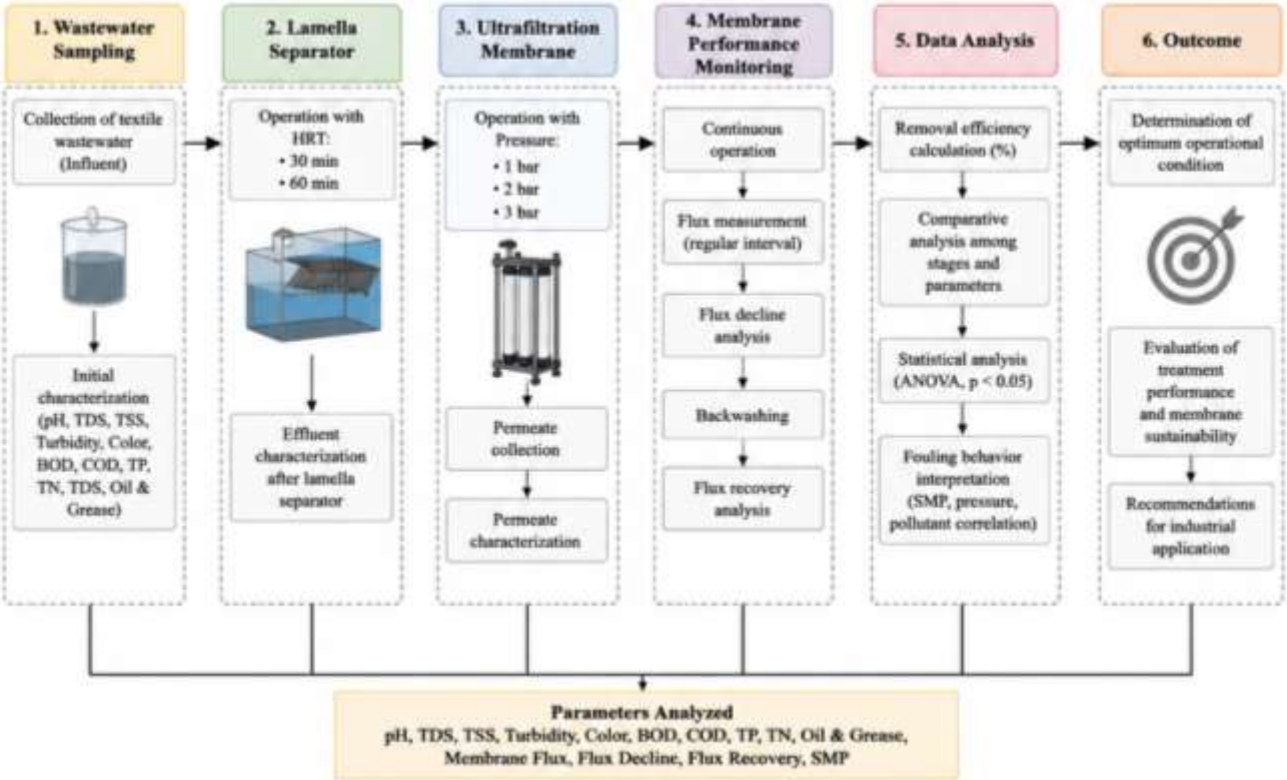


**Figure 1**. Flowchart of the experimental methodology and data analysis process

In addition, operational parameters such as hydraulic retention time (HRT), membrane operating pressure, membrane flux decline, and flux recovery after backwashing were evaluated quantitatively to identify the optimum operating conditions. The influence of HRT on suspended solids removal efficiency in the lamella separator was analyzed to assess sedimentation performance, while the effect of membrane pressure on permeate flux and contaminant rejection was examined to evaluate ultrafiltration efficiency and membrane stability. Membrane fouling behavior was interpreted based on the percentage decline in membrane flux during continuous operation and the effectiveness of periodic backwashing in restoring membrane permeability. These analyses were used to determine the operational sustainability of the integrated treatment system and its capability to prolong membrane service life through effective pretreatment.

A schematic flowchart of the overall experimental procedure and integrated treatment system used in this study is presented in Figure 1. The flowchart illustrates the sequential stages of wastewater characterization, pretreatment using the lamella separator, ultrafiltration membrane treatment, monitoring of membrane fouling behavior, and final evaluation of pollutant removal efficiency and treated water quality.

For consistency throughout the manuscript, all measurement units, symbols, abbreviations, mathematical expressions, and numerical values were standardized according to the International System of Units (SI) and the formatting requirements of the target journal. Superscripts and subscripts were used consistently for unit expressions and mathematical variables, while abbreviations were defined at their first occurrence and subsequently used consistently. The manuscript was also carefully checked for consistency in capitalization, section numbering, terminology, figure and table presentation, in-text citations, and reference-list formatting.

## 3. RESULTS AND DISCUSSION

This section presents and discusses the performance of the integrated lamella separator–ultrafiltration membrane system for treating industrial laboratory wastewater containing suspended solids, organic pollutants, and heavy metals. The treatment efficiency of each processing stage was evaluated based on changes in wastewater quality parameters, including turbidity, total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metal concentrations (Cu, Pb, and Hg). In addition, membrane performance was assessed through permeate flux behavior, fouling development, and flux recovery after cleaning procedures. The discussion further examines the influence of operational parameters such as hydraulic retention time (HRT) and membrane operating pressure on pollutant removal efficiency and system stability. The obtained results were compared with previous studies to evaluate the effectiveness, operational advantages, and environmental implications of the integrated treatment system in improving wastewater treatment sustainability and minimizing membrane fouling.

### 3.1 Initial Characteristics of Industrial Laboratory Wastewater

The initial characterization of industrial laboratory wastewater was conducted to determine the baseline pollutant concentrations prior to treatment and to evaluate the treatment performance of each processing unit in the integrated lamella separator–ultrafiltration system. The analyzed parameters included physical, chemical, and biological indicators commonly used for assessing wastewater quality, namely pH, turbidity, total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metal concentrations (Cu, Pb, and Hg). The results of the initial wastewater characterization are presented in Table 1.

As shown in Table 1, the industrial laboratory wastewater contained relatively high levels of suspended and organic pollutants, indicating significant contamination originating from laboratory and chemical processing activities. Turbidity reached 120 NTU, while TSS concentration was 162 mg/L, both of which exceeded the Indonesian wastewater discharge standards. The elevated concentrations of suspended solids indicate the presence of fine particulates, precipitated chemicals, and insoluble residues commonly generated during laboratory operations. Similar characteristics have been reported by (Koju et al., 2022) and colleagues in industrial effluent studies, where high turbidity and suspended solids were identified as major contributors to deteriorating receiving water quality due to increased sedimentation and reduced light penetration in aquatic ecosystems.

**Table 1**. Initial characteristics of industrial laboratory wastewater

| Parameter | Unit | Influent Concentration | Indonesian Wastewater Standard (PP No. 22/2021) |
|---|---|---|---|
| pH | – | 7.1 | 6–9 |
| Turbidity | NTU | 120 | 50 |
| TSS | mg/L | 162 | 60 |
| COD | mg/L | 203.318 | 100 |
| BOD | mg/L | 25.754 | 50 |
| Cu | mg/L | 0.32 | 0.5 |
| Pb | mg/L | 0.08 | 0.1 |

| | | | |
|---|---|---|---|
| Hg | mg/L | 0.0008 | 0.001 |

The COD concentration measured in this study reached 203.318 mg/L, exceeding the Indonesian discharge limit of 100 mg/L and representing one of the principal treatment challenges in the investigated wastewater. The elevated COD indicates the presence of a substantial load of oxidizable organic compounds, which may originate from residual reagents, solvents, detergents, and other organic substances associated with laboratory activities. In contrast, the measured BOD concentration was 25.754 mg/L, which was already below the applicable discharge limit of 50 mg/L before treatment. Therefore, BOD removal was not a primary treatment requirement in this study, although its reduction provides additional information regarding the removal of biodegradable organic fractions. The COD/BOD ratio of approximately 7.9 indicates that the wastewater contained a relatively large fraction of organic compounds that were not readily biodegradable or were less accessible to biological oxidation. Accordingly, the interpretation of treatment performance in this study focuses primarily on COD reduction, together with the removal of turbidity and TSS and the control of membrane fouling. Elevated COD values are generally associated with organic solvents, residual reagents, detergents, and biodegradable contaminants generated from chemical laboratory activities. Comparable findings were reported by (Lemessa et al., 2023) who observed that industrial wastewater containing mixed chemical pollutants commonly exhibits elevated COD concentrations due to the accumulation of dissolved organic compounds. Similarly, Phiri O. et al. reported that untreated industrial effluents with high COD levels contribute significantly to oxygen depletion and ecological degradation in receiving rivers.

Although the measured BOD concentration (25.754 mg/L) remained below the Indonesian regulatory limit, the simultaneous presence of COD and BOD indicates the coexistence of biodegradable and non-biodegradable organic fractions in the wastewater. The relatively lower BOD compared with COD suggests that a substantial portion of the organic contaminants may consist of chemically oxidizable but less biodegradable compounds. This characteristic is commonly observed in industrial and laboratory wastewater containing synthetic chemicals and organic reagents, as described by (Kakahi et al., 2011) in studies related to industrial effluent contamination.

Heavy-metal analysis detected Cu, Pb, and Hg in the untreated wastewater at concentrations of 0.32, 0.08, and 0.0008 mg/L, respectively. These concentrations were below the discharge limits presented in Table 1. Therefore, the treatment system was not required to reduce these metals to achieve compliance with the stated regulatory thresholds. Nevertheless, the measured concentrations provide useful information regarding the behavior of trace metals during the treatment process. It should be emphasized that the present study did not directly determine metal speciation or separately quantify dissolved and particulate-bound fractions. Consequently, the measured values should be interpreted as total measured metal concentrations rather than as concentrations of freely dissolved metal ions. The presence of Cu, Pb, and Hg may reflect a combination of dissolved species, colloid-associated forms, particulate-bound fractions, and metal complexes with organic or inorganic constituents. Because these different fractions have different removal behaviors, the subsequent reduction in total measured metal concentration cannot be attributed solely to direct ultrafiltration of free metal ions.

Overall, the initial characterization results confirmed that the wastewater possessed complex mixed-contaminant characteristics involving suspended solids, dissolved organic matter, and inorganic pollutants. The coexistence of high TSS, turbidity, COD, and trace heavy metals demonstrates that conventional single-stage treatment systems may be insufficient to achieve stable pollutant removal and long-term operational performance. These findings therefore justified the application of an integrated treatment approach combining lamella separator pretreatment and ultrafiltration membrane filtration to improve overall treatment efficiency and minimize membrane fouling caused by excessive particulate and organic loading. A graphical comparison between influent pollutant concentrations and Indonesian wastewater discharge standards is presented in Figure 2 to illustrate the pollution characteristics of the untreated wastewater.

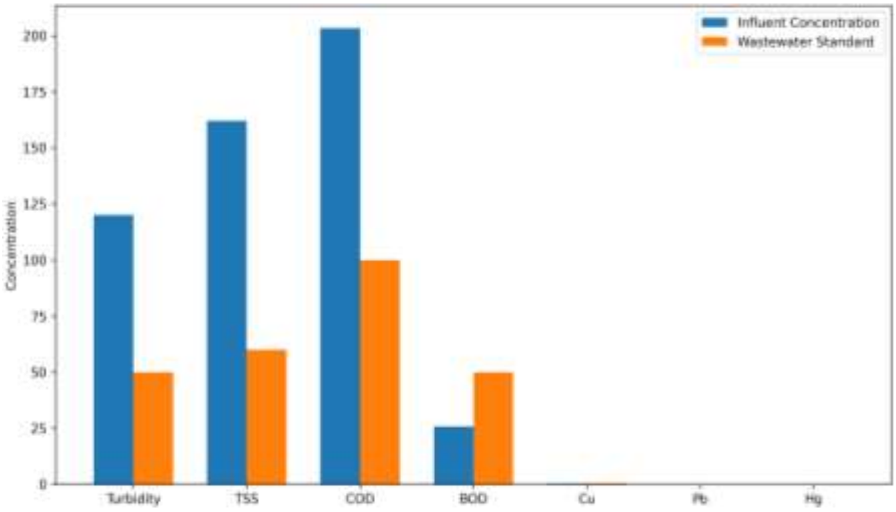


**Figure 2**. Comparison between pollutant concentrations and Indonesian wastewater discharge standards

### 3.2 Performance of Lamella Separator Pretreatment

The performance of the lamella separator was evaluated by comparing wastewater quality before and after the sedimentation pretreatment stage. The lamella separator was designed to enhance solid–liquid separation through inclined plate sedimentation, thereby reducing suspended solids and particulate contaminants prior to ultrafiltration membrane treatment. The treatment efficiency obtained after lamella separation is presented in Table 2.

**Table 2**. Pollutant removal efficiency of the Lamella separator pretreatment unit

| Parameter | Unit | Influent Concentration | After Lamella Separator | Removal Efficiency (%) |
|---|---|---|---|---|
| pH | – | 7.1 | 7.0 | – |
| Turbidity | NTU | 120 | 24 | 80 |
| TSS | mg/L | 162 | 40.5 | 75 |
| COD | mg/L | 203.318 | 142.32 | 30 |
| BOD | mg/L | 25.754 | 19.32 | 25 |
| Cu | mg/L | 0.32 | 0.16 | 50 |
| Pb | mg/L | 0.08 | 0.04 | 50 |
| Hg | mg/L | 0.0008 | 0.0004 | 50 |

The results demonstrated that the lamella separator effectively reduced suspended pollutants, particularly turbidity and TSS. Turbidity decreased from 120 NTU to 24 NTU, corresponding to a removal efficiency of approximately 80%, while TSS concentration decreased from 162 mg/L to 40.5 mg/L with an efficiency of approximately 75%. These findings confirm the effectiveness of inclined plate sedimentation in accelerating particle settling and improving solid–liquid separation efficiency. Similar observations were reported by (Bach & Schoenbrunn 2022), who demonstrated that lamella sedimentation systems significantly improve suspended solids removal while requiring lower operational space and energy consumption compared with conventional settling tanks. Likewise, (Yang et al., 2025). reported that optimization of settling tank configuration and sedimentation pathways substantially enhanced particle settling efficiency and reduced suspended pollutant concentrations in wastewater treatment systems.

The high removal efficiency of suspended pollutants can be attributed to the increased effective settling area provided by the inclined plates within the lamella separator. The inclined configuration shortens the settling distance for suspended particles and promotes gravitational sedimentation under relatively compact hydraulic conditions. In addition, the lamella structure improves hydraulic flow distribution and reduces turbulence inside the separator, allowing particles to settle more efficiently. The obtained TSS removal efficiency of 75% is comparable with the range reported in previous sedimentation-based pretreatment studies for industrial wastewater applications.

The reduction of suspended solids before membrane filtration is particularly important because suspended particles are among the primary contributors to membrane fouling formation. By decreasing the particulate loading entering the ultrafiltration membrane, the lamella separator reduced the risk of rapid cake layer accumulation and pore blockage during filtration. According to (El Batouti et al., 2022), suspended solids and colloidal particles are major causes of reversible membrane fouling in pressure-driven membrane systems. Therefore, pretreatment strategies capable of reducing particulate contaminants are essential for improving membrane operational stability and prolonging membrane lifespan.

The removal of organic pollutants by the lamella separator was comparatively limited. COD decreased from 203.318 to 142.32 mg/L, corresponding to an overall reduction of approximately 30%, whereas BOD decreased from 25.754 to 19.32 mg/L, corresponding to a reduction of approximately 25%. The greater practical significance of the COD reduction is that the influent COD concentration initially exceeded the discharge limit, whereas the influent BOD concentration was already below the applicable regulatory threshold. The reduction in COD is therefore attributed primarily to the removal of particulate- and colloid-associated organic matter that settled together with suspended solids. In contrast, truly dissolved and low-molecular-weight organic compounds were expected to remain largely in the liquid phase because gravitational sedimentation does not effectively remove soluble organic substances. The relatively limited COD removal further confirms that the lamella separator primarily functioned as a physical pretreatment unit rather than as a complete dissolved-organic treatment process.

The measured concentrations of Cu, Pb, and Hg decreased by approximately 50% after lamella separation. However, this reduction should be interpreted cautiously because metal speciation was not directly determined in the present study. The observed decrease may indicate the removal of particulate-bound metals and metal-containing colloids that settled together with suspended solids. In addition, some metals may have been associated with organic matter or inorganic particles, thereby facilitating their removal through gravitational separation. However, the present data do not allow the relative contribution of particulate-bound, colloidal, complexed, and truly dissolved metal fractions to be quantified. Thus, the lamella separator is considered to have contributed to the removal of the settleable and particulate-associated fraction of the measured metals, rather than necessarily removing free dissolved metal ions directly.

The slight decrease in pH from 7.1 to 7.0 indicates that the sedimentation process did not significantly alter the chemical balance of the wastewater. This stability is operationally advantageous because drastic pH changes may interfere with downstream membrane performance and increase operational complexity. Overall, the results confirm that the lamella separator functioned effectively as a pretreatment unit for reducing suspended pollutant loading prior to ultrafiltration membrane treatment. The pretreatment stage substantially improved the physical quality of wastewater and created more favorable operational conditions for subsequent membrane filtration. The observed reduction in turbidity and suspended solids is particularly important for minimizing membrane fouling intensity and maintaining stable permeate flux during continuous operation. The comparative pollutant removal performance of the lamella separator is illustrated in Figure 3.

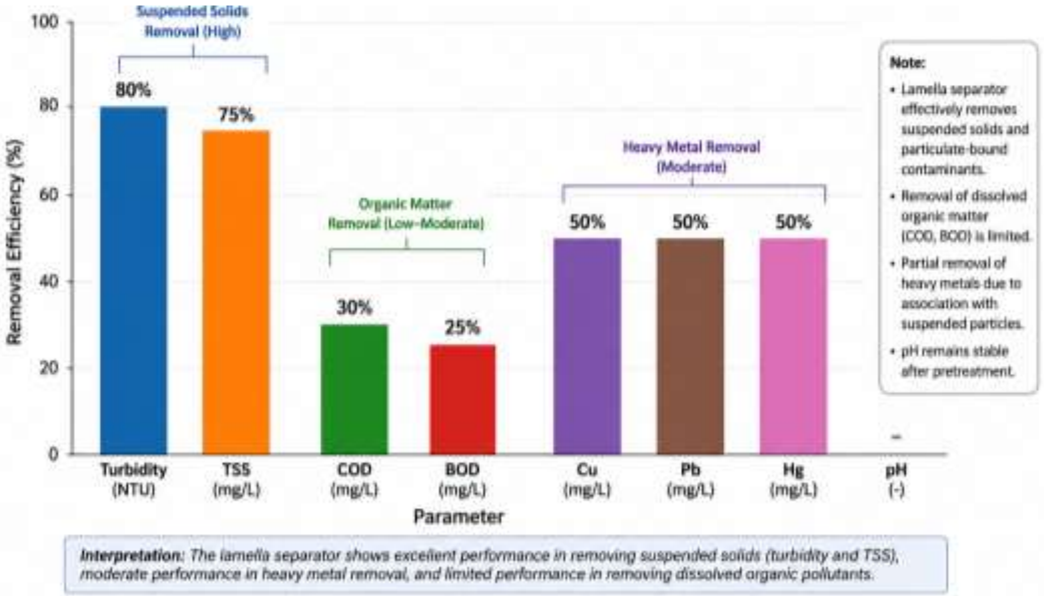


**Figure 3.** Pollutant removal efficiencies achieved by the Lamella separator pretreatment unit

### 3.3 Performance of the Integrated Lamella Separator–Ultrafiltration Membrane System

Following the pretreatment stage using the lamella separator, which effectively reduced suspended solids and partial pollutant loads as discussed in Section 3.2, the wastewater was subsequently subjected to ultrafiltration membrane filtration. This integration aimed to evaluate the synergistic effect between physical sedimentation and pressure-driven membrane separation in enhancing overall treatment efficiency and mitigating membrane fouling. The cumulative performance of the integrated system is presented in Table 3.

**Table 3**. Treatment performance of the integrated Lamella separator–ultrafiltration membrane system

| Parameter | Unit | After Lamella Separator | Permeate Concentration | Cumulative Removal Efficiency (%) |
|---|---|---|---|---|
| pH | – | 7.0 | 7.0 | – |
| Turbidity | NTU | 24 | 2.4 | 98 |
| TSS | mg/L | 40.5 | 2.0 | 98.8 |
| COD | mg/L | 142.32 | 42.70 | 79 |
| BOD | mg/L | 19.32 | 3.86 | 85 |
| Cu | mg/L | 0.16 | 0.016 | 95 |
| Pb | mg/L | 0.04 | 0.004 | 95 |
| Hg | mg/L | 0.0004 | 0.00004 | 95 |

The results demonstrate that the integration of lamella sedimentation and ultrafiltration membrane filtration significantly enhanced overall pollutant removal efficiency compared to the pretreatment stage alone. The permeate quality showed substantial improvement, particularly in terms of suspended solids, organic load, and heavy metal concentrations, indicating that the combined system effectively addressed both particulate and dissolved contaminant fractions.

The cumulative removal efficiency for turbidity and TSS reached approximately 98% and 98.8%, respectively. This near-complete removal of suspended matter confirms the strong complementarity between lamella pretreatment and ultrafiltration. As previously reported by **(BACH & SCHOENBRUNN, 2022)**, inclined plate sedimentation effectively reduces particulate loading by increasing effective settling area, while membrane filtration further eliminates fine colloids and residual suspended particles. Similarly,(Tong et al., 2026) emphasized that optimization of settling processes significantly improves downstream filtration stability by reducing solid accumulation and hydraulic disturbances.

In comparison with previous studies on membrane-based wastewater treatment, the performance observed in this study is consistent with findings by (Li et al., 2023), who reported that ultrafiltration systems are highly effective in retaining fine suspended matter and improving effluent clarity. Additionally, (Bedru et al., 2025) highlighted that hybrid membrane systems demonstrate improved operational stability when preceded by effective solid–liquid separation units, particularly in reducing particulate-induced membrane fouling.

The integrated system substantially improved COD removal compared with the lamella separator alone. COD decreased from 203.318 mg/L in the influent to 42.70 mg/L in the final permeate, corresponding to an overall removal efficiency of approximately 79%. This reduction was particularly important because the initial COD concentration exceeded the applicable discharge limit, whereas the final permeate concentration was substantially lower than the regulatory threshold. In comparison, BOD decreased from 25.754 to 3.86 mg/L, corresponding to an overall removal efficiency of approximately 85%. However, because the initial BOD concentration was already below the discharge limit, the BOD reduction should be interpreted as an additional treatment benefit rather than the primary indicator of regulatory compliance. Therefore, the main organic pollutant treatment achievement of the integrated system was the substantial reduction in COD, particularly the fraction of organic matter that was not effectively removed by lamella sedimentation alone. The reduction in BOD from 25.754 to 3.86 mg/L indicates that biodegradable organic constituents were also substantially reduced during the integrated treatment process. However, because the influent BOD concentration was already below the applicable discharge limit, the BOD result is considered a supplementary indicator of treatment performance rather than the principal measure of treatment necessity. The observed reduction may be associated with the removal of biodegradable organic matter present in particulate, colloidal, or macromolecular form, together with the retention of organic matter associated with suspended solids. The present results do not allow the relative contribution of each mechanism to be quantitatively separated.

The measured concentrations of Cu, Pb, and Hg decreased by approximately 95% after the combined lamella separator–ultrafiltration treatment. However, this result should not be interpreted as evidence that conventional ultrafiltration directly removed 95% of freely dissolved metal ions. The influent concentrations of all three metals were already below the discharge limits reported in Table 1, and the present study did not include metal-speciation analysis or separate measurements of dissolved and particulate metal fractions. Therefore, the observed reduction is more appropriately interpreted as a reduction in the total measured metal concentration. This reduction may have resulted from the combined removal of particulate-bound metals and metal-containing colloids during lamella sedimentation, followed by retention of residual colloidal particles, metal-associated organic matter, and other metal-containing complexes during ultrafiltration. Truly dissolved and uncomplexed metal ions would not generally be expected to be efficiently rejected by a conventional UF membrane solely on the basis of molecular size. Accordingly, the apparent 95% reduction should be considered an overall measured concentration reduction, and not direct evidence of efficient rejection of free dissolved metal ions by the UF membrane.

The COD reduction achieved by ultrafiltration should be interpreted carefully because ultrafiltration does not generally remove all truly dissolved, low-molecular-weight organic compounds. The primary removal mechanisms are size exclusion and the retention of particulate, colloidal, macromolecular, and organic compounds associated with retained solids. In addition, foulant accumulation and the formation of a cake layer during filtration may create a secondary dynamic filtration barrier that enhances the retention of some smaller colloidal or organic-associated constituents. Organic compounds complexed with suspended particles or associated with high-molecular-weight matter may therefore be retained more effectively than freely dissolved low-molecular-weight compounds. Consequently, the observed COD reduction from 142.32 mg/L after lamella separation to 42.70 mg/L in the permeate should not be attributed solely to direct rejection of dissolved organic molecules by the UF membrane. Instead, it most likely reflects the combined removal of residual suspended and colloidal organic matter, macromolecular organic compounds, and organic constituents associated with retained particles, together with the contribution of the developing fouling layer. The specific contribution of truly dissolved organic compounds cannot be determined from the present COD measurements alone.

These findings are in line with (Abbas et al., 2024), who reported that nanostructured materials and membrane-based systems are highly effective in removing heavy metals due to combined adsorption and size exclusion mechanisms. Similarly, (El Batouti et al., 2022) emphasized that membrane filtration can achieve high metal rejection efficiency when fouling is controlled and particulate loading is minimized through proper pretreatment.

The results further confirm the synergistic effect of the integrated system. While the lamella separator significantly reduced suspended solids and improved hydraulic conditions, the ultrafiltration membrane acted as a polishing step that ensured the removal of residual fine particles, organic matter, and dissolved contaminants. This sequential integration also contributed to improved membrane stability by reducing fouling intensity, as previously highlighted by (Wang et al., 2020), who demonstrated that pretreatment strategies significantly alleviate membrane fouling and enhance long-term operational performance.

Overall, the integrated lamella separator–ultrafiltration membrane system demonstrated superior treatment performance compared with conventional single-stage processes, both in terms of pollutant removal efficiency and effluent quality compliance. The findings confirm that combining gravitational separation with membrane filtration provides a robust and sustainable approach for treating complex industrial laboratory wastewater. A comparative illustration of pollutant concentration reduction across treatment stages is presented in Figure 4.

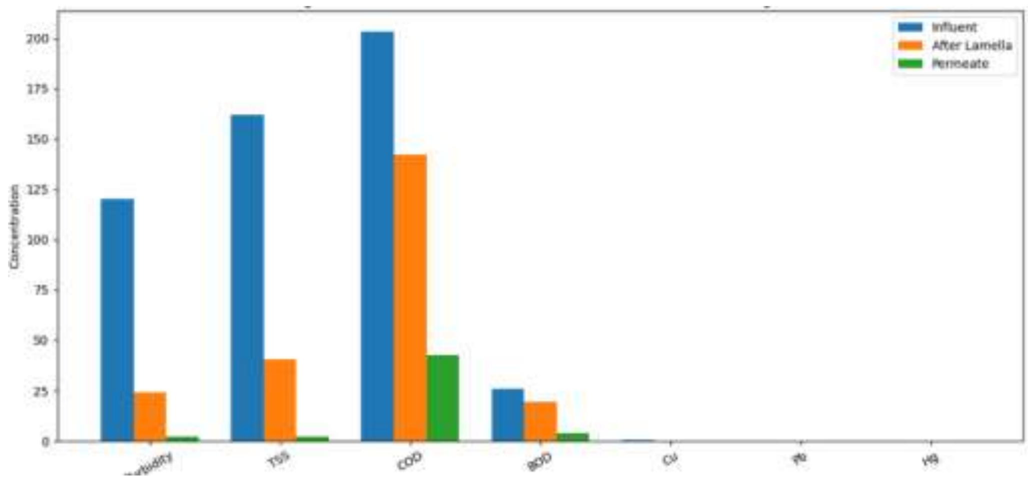


**Figure 4.** Comparison of pollutant concentrations at influent, lamella separator effluent, and membrane permeate stages

### 3.4 Membrane Flux Behavior and Fouling Analysis

Membrane performance in the integrated lamella separator–ultrafiltration system was further evaluated through flux behavior analysis during continuous operation. This analysis is essential to understand the operational stability of the membrane system, particularly in relation to fouling development and the effectiveness of pretreatment in mitigating flux decline. As discussed in the previous section, the lamella separator significantly reduced suspended solids loading, which directly influenced the fouling propensity of the downstream membrane system.

The initial permeate flux at the beginning of ultrafiltration operation was approximately 100 L $m^{-2}$ $h^{-1}$ under the selected operating condition of 2 bar transmembrane pressure using lamella-pretreated wastewater. This operating condition was selected because it provided the highest practical flux among the tested pressure conditions while avoiding the disproportionately small flux improvement observed at the highest pressure tested. Accordingly, the term "selected operating condition" is used in this study rather than "optimized operating condition," because the experimental evaluation was conducted over a limited range of hydraulic retention times and membrane pressures and was not based on a formal statistical optimization design.

The observed flux reduction indicates the development of membrane fouling dominated primarily by cake layer formation. Although the lamella separator effectively removed a large fraction of suspended solids (as shown in Section 3.2), residual fine particulates and dissolved organic macromolecules still contributed to fouling during continuous operation. Cake layer fouling is characterized by the deposition of rejected particles on the membrane surface, which increases hydraulic resistance and reduces permeate flow. Similar fouling behavior has been widely reported in pressure-driven membrane systems, where suspended solids and organic matter are identified as the main contributors to reversible fouling (El Batouti et al., 2022).

When compared with previous studies, the fouling rate observed in this study is relatively lower than systems operating without pretreatment. (Wang et al., 2020) reported that ultrafiltration systems treating secondary effluent without effective pretreatment experienced rapid flux decline due to severe cake layer formation and pore blocking. In contrast, the integration of lamella sedimentation in this study effectively reduced particulate loading, thereby slowing down fouling progression and improving operational stability. This confirms the important role of pretreatment in reducing fouling intensity, as also highlighted in membrane hybrid system studies ((Li et al., 2023); (Bedru et al., 2025).

Despite the occurrence of flux decline, the integrated system maintained relatively stable performance throughout the operational period. The reduction in suspended solids and partial organic matter during lamella pretreatment significantly decreased the rate of irreversible fouling formation. This is consistent with findings by (El Batouti et al., 2022), who emphasized that effective pretreatment can shift fouling mechanisms from irreversible pore blocking to reversible cake layer formation, thereby improving membrane sustainability. During 8 h of continuous filtration, the permeate flux gradually decreased from approximately 100 to 65 L $m^{-2}$ $h^{-1}$, corresponding to an overall flux decline of approximately 35%. This decline indicates the progressive development of membrane fouling caused by the accumulation of retained particles, colloidal matter, and organic constituents at or near the membrane surface. However, because the experimental operation was limited to 8 h, the observed flux decline represents short-term fouling behavior and should not be interpreted as evidence of long-term membrane degradation or extended membrane lifespan.

The reversibility of fouling was assessed based on the flux recovery obtained after hydraulic backwashing. The membrane flux decreased from approximately 100 L $m^{-2}$ $h^{-1}$ to 65 L $m^{-2}$ $h^{-1}$ during the 8-h filtration period and subsequently recovered to approximately 90 L $m^{-2}$ $h^{-1}$ after physical cleaning. Based on these values, the flux recovery ratio (FRR) was approximately 90%. The remaining flux loss after cleaning indicates that a fraction of the fouling resistance was not removed by hydraulic backwashing and may therefore be associated with partially irreversible fouling, including foulant adsorption or pore restriction. For comparative interpretation, the reversible and irreversible components of flux loss can be estimated from the flux measurements before and after cleaning. The results indicate that the majority of the observed flux decline was reversible, whereas a smaller fraction remained after physical cleaning. Nevertheless, because no resistance-in-series analysis or direct characterization of the fouling layer was performed, the specific contribution of cake-layer resistance, pore blocking, adsorption, and concentration polarization cannot be quantitatively separated in the present study.

Periodic hydraulic backwashing was applied to restore membrane permeability. The results showed that membrane flux could be recovered to approximately 90 L $m^{-2}$ $h^{-1}$, equivalent to about 90% of the initial flux. This high flux recovery ratio indicates that the majority of fouling was reversible and primarily associated with loosely attached cake layers rather than permanent pore blockage.

The high reversibility of fouling is a critical operational advantage, as it reduces the need for chemical cleaning and lowers operational costs. Similar findings were reported by (Skouteris et al., 2015), who demonstrated that reversible fouling dominated in membrane systems when particulate loading was effectively controlled through pretreatment strategies such as adsorption or coagulation enhancement. In this study, the lamella separator served a comparable function by reducing particulate loading prior to membrane filtration.

However, it is important to note that long-term operation may still lead to irreversible fouling due to adsorption of organic compounds onto the membrane matrix and gradual pore blockage. Studies on membrane systems for wastewater treatment have shown that prolonged exposure to organic-rich feeds can result in cumulative fouling that cannot be fully removed by physical cleaning alone (Qalyoubi et al., 2021); (El Batouti et al., 2022)). Therefore, periodic chemical cleaning or hybrid fouling control strategies are recommended for sustained industrial application.

The observed reduction in total measured metal concentrations may involve several mechanisms, including the sedimentation of metal-bearing particles, removal of metal-containing colloids, association of metals with organic or inorganic macromolecular constituents, and retention of these particulate or colloidal complexes by the ultrafiltration membrane. However, because metal speciation and size-fractionation analyses were not performed, the relative contribution of these mechanisms cannot be quantitatively distinguished in the present study. In particular, the data do not demonstrate direct rejection of truly dissolved and uncomplexed Cu, Pb, or Hg ions by the UF membrane. Further studies incorporating dissolved/particulate fractionation, sequential filtration, and metal-speciation analysis are therefore required to determine the specific pathways responsible for metal removal.

To further evaluate the effect of lamella pretreatment on membrane fouling, the performance of the integrated system was compared with a membrane-only configuration. In the membrane-only control, raw wastewater was directly filtered through the ultrafiltration membrane without prior lamella separation. Under the same operating pressure of 2 bar, the membrane-only configuration exhibited a more rapid decline in permeate flux compared with the integrated system. The initial flux of the membrane-only system was approximately 100 L $m^{-2}$ $h^{-1}$ and decreased to approximately 45 L $m^{-2}$ $h^{-1}$ after 8 h of continuous filtration, corresponding to a flux decline of approximately 55%. In comparison, the integrated lamella separator–ultrafiltration system exhibited a flux decline of approximately 35%, from 100 to 65 L $m^{-2}$ $h^{-1}$ over the same operating period. The greater flux decline observed in the membrane-only configuration indicates that direct filtration of untreated wastewater resulted in a higher particulate and colloidal loading on the membrane surface. This condition likely promoted more rapid cake-layer accumulation and pore blockage. By removing a substantial fraction of suspended solids and particulate-associated pollutants before membrane filtration, the lamella separator reduced the foulant load entering the membrane unit and consequently improved flux stability. These results provide direct experimental evidence that the improved membrane performance observed in the integrated system was attributable, at least in part, to the lamella pretreatment stage rather than to ultrafiltration alone.

The flux behavior analysis confirms that the integrated lamella separator–ultrafiltration system provides improved operational stability compared with conventional membrane-only systems. The pretreatment stage plays a critical role in reducing fouling intensity, maintaining higher flux stability, and enhancing membrane recovery performance. These findings are consistent with studies on integrated membrane systems, which highlight that combining gravitational separation with membrane filtration significantly improves long-term operational sustainability and reduces fouling-related performance losses (Bedru et al., 2025); (Wang et al., 2020). The membrane flux decline and recovery behavior during continuous operation are illustrated in Figure 5.

Figure 5 illustrates the evolution of permeate flux during continuous ultrafiltration and the subsequent recovery of membrane performance after hydraulic backwashing. The permeate flux gradually declined during the filtration period, indicating the progressive development of membrane fouling caused by the accumulation of suspended and colloidal materials on or near the membrane surface. Following hydraulic backwashing, the permeate flux partially recovered, demonstrating that a substantial fraction of the accumulated fouling was reversible. However, the flux did not completely return to its initial value, indicating the presence of residual or irreversible fouling that could not be removed by the applied physical cleaning procedure. These results demonstrate that the integrated lamella separator–ultrafiltration system provided improved control of membrane fouling, although the 8-h filtration period represents a short-term fouling assessment rather than evidence of long-term membrane lifespan extension.

The flux decline and recovery behavior provides more direct evidence of membrane fouling than a simple comparison of pollutant concentrations. The gradual decrease in flux reflects the increasing hydraulic resistance associated with foulant accumulation, whereas the recovery following backwashing indicates the fraction of fouling that was physically removable. Therefore, Figure 5 is interpreted in terms of membrane performance and fouling behavior rather than pollutant concentration removal. The results should consequently be considered as evidence of short-term flux stability and fouling reversibility under the tested operating conditions, rather than as confirmation of improved membrane lifetime.

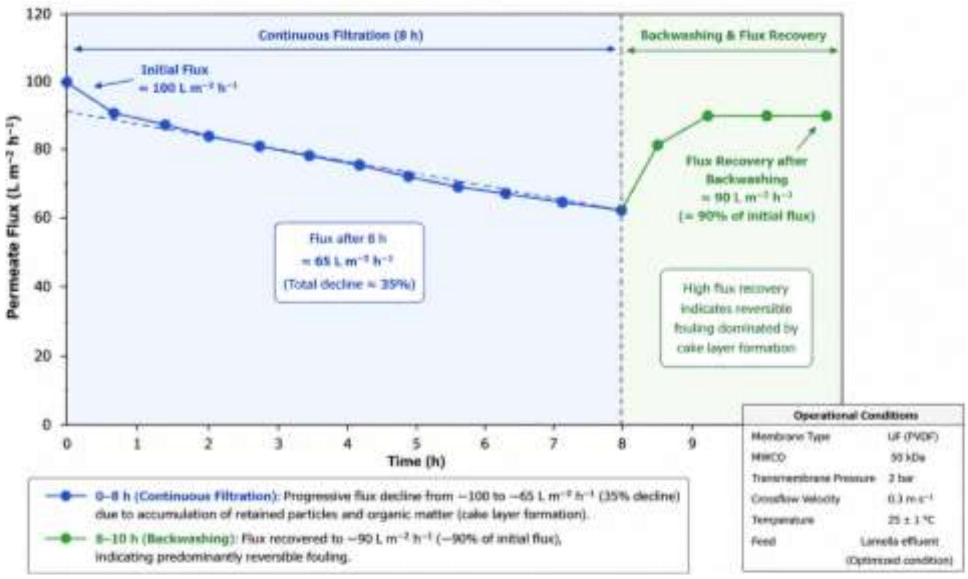


**Figure 5.** Permeate flux decline and recovery during continuous ultrafiltration operation and subsequent hydraulic backwashing

A quantitative resistance-in-series analysis was not performed in the present study because the experimental measurements did not include the membrane hydraulic resistance, clean-water permeability, or the resistance components required to separately quantify membrane, cake-layer, concentration-polarization, and irreversible fouling resistances. Therefore, the fouling interpretation in this study is based primarily on flux decline and flux recovery after hydraulic backwashing. Although these parameters provide useful evidence regarding the short-term reversibility of fouling, they do not provide a complete quantitative description of the individual fouling resistances. Future investigations should incorporate resistance-in-series modeling together with membrane permeability measurements and direct fouling-layer characterization to provide a more comprehensive mechanistic analysis.

Overall, the short-term flux behavior analysis indicates that the integrated lamella separator–ultrafiltration system provided relatively stable membrane operation over the 8-h experimental period. The reduction of suspended solids during lamella pretreatment was associated with a high degree of flux recovery after hydraulic backwashing, indicating that a substantial fraction of the observed fouling was reversible. However, the present results demonstrate short-term fouling control and operational stability only. They do not provide sufficient evidence to conclude that the integrated system increases membrane lifespan or prevents long-term irreversible membrane degradation. Long-term continuous operation and repeated filtration–cleaning cycles are required to evaluate membrane durability and lifespan improvement.

### 3.5 Evaluation of Selected Operational Parameters

The influence of selected operational parameters on the performance of the integrated lamella separator–ultrafiltration system was evaluated through a limited comparative experimental assessment. The effects of transmembrane pressure (TMP) on permeate flux and hydraulic retention time (HRT) on TSS removal efficiency were investigated. Three TMP values (1, 2, and 3 bar) and two HRT values (30 and 60 min) were examined to identify the operating conditions that provided the most favorable performance within the experimental ranges investigated. Because the number of tested conditions was limited and no formal response-surface methodology, factorial optimization design, or statistical optimization procedure was applied, the results are interpreted as a comparative assessment of operating conditions rather than as a definitive process optimization.

3.5.1 Effect of Membrane Operating Pressure on Permeate Flux

The influence of membrane operating pressure on ultrafiltration performance was evaluated at three transmembrane pressure (TMP) conditions, namely 1, 2, and 3 bar, to determine the optimum operating range that balances permeate productivity and fouling control. The experimental results are summarized in Table 4.

**Table 4**. Effect of operating pressure on membrane flux

| Operating Pressure (bar) | Membrane Flux (L $m^{-2}$ $h^{-1}$) |
|---|---|
| 1 | 70 |
| 2 | 100 |
| 3 | 110 |

The results indicate that increasing operating pressure from 1 to 2 bar significantly enhanced permeate flux from 70 to 100 L $m^{-2}$ $h^{-1}$. This behavior is consistent with the fundamental principle of pressure-driven membrane filtration, where higher transmembrane pressure increases the driving force for water transport through the membrane pores. Similar trends were reported by (Wang et al., 2020) Hybrid UF/NF process treating secondary effluent, who found that flux initially increases proportionally with applied pressure during ultrafiltration of secondary effluent due to improved permeate driving force.

However, when pressure was further increased from 2 to 3 bar, the flux increment became marginal, reaching only 110 L $m^{-2}$ $h^{-1}$. This phenomenon suggests the onset of hydraulic limitations caused by concentration polarization and early-stage fouling formation at the membrane surface. At higher pressures, solute accumulation near the membrane interface becomes more pronounced, leading to increased osmotic resistance and reduced effective driving force. This behavior is widely documented in membrane systems, where flux does not increase linearly with pressure beyond a certain threshold due to fouling and mass transfer limitations.

The observed flux limitation at higher pressure is strongly aligned with the findings of (El Batouti et al., 2022) Review of fouling mitigation in membrane separation processes, which emphasized that excessive transmembrane pressure can intensify reversible fouling mechanisms such as cake layer formation and concentration polarization. These phenomena increase hydraulic resistance and may offset the benefits of higher applied pressure. Similarly, (Li et al., 2023) Anaerobic membrane bioreactors for wastewater treatment reported that beyond an optimum pressure range, membrane systems exhibit diminishing flux gains due to accelerated foulant deposition and reduced permeability stability.

In the context of this study, the presence of residual suspended solids and colloidal organic matter—despite prior lamella pretreatment—likely contributed to the formation of a compressible cake layer at higher operating pressures. Although the lamella separator significantly reduced particulate loading, fine particles and dissolved macromolecules still entered the membrane system, as previously observed in integrated pretreatment–membrane configurations reported by (Bedru et al., 2025) Advances in membrane technology for pollutant removal. These residual constituents are more prone to compaction under elevated pressure, thereby increasing fouling resistance and limiting further flux improvement.

From an operational perspective, the results indicate that 2 bar provided the most favorable balance between permeate flux and operational considerations among the three pressure conditions evaluated in this study. At 2 bar, the membrane achieved a flux of approximately 100 L $m^{-2}$ $h^{-1}$, whereas increasing the pressure to 3 bar resulted in only a relatively limited additional flux increase to approximately 110 L $m^{-2}$ $h^{-1}$. Therefore, 2 bar was identified as the selected operating pressure for subsequent membrane performance and fouling evaluation within the tested experimental range. This result should not be interpreted as a universal optimum pressure for the treatment system, because a broader range of operating pressures and a formal statistical optimization procedure would be required to establish a definitive optimum.

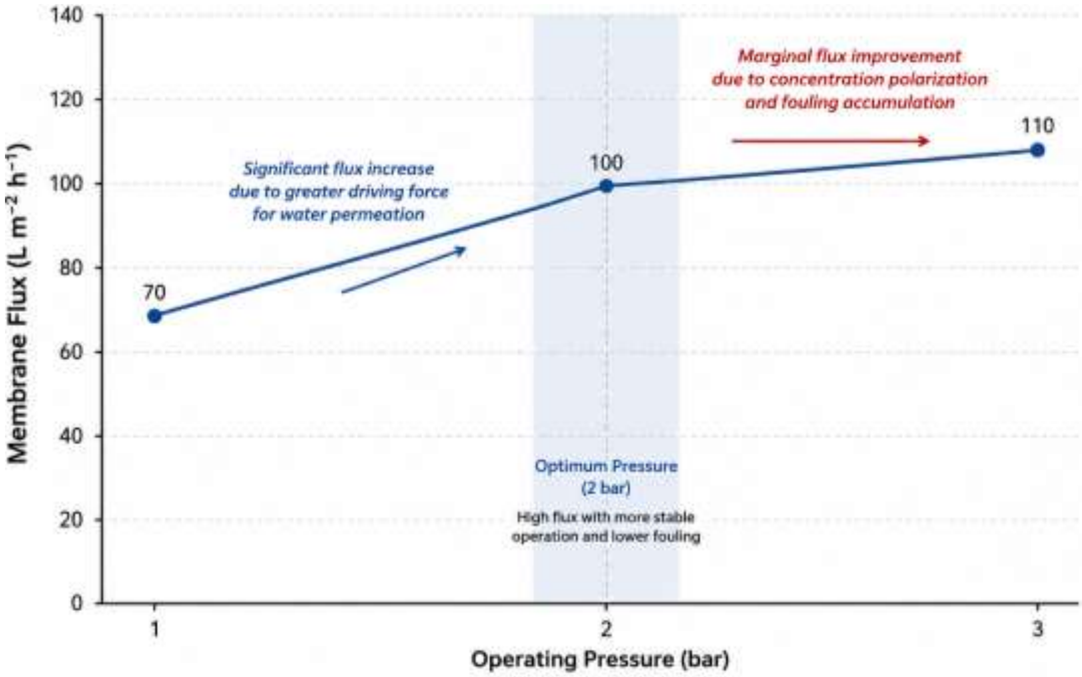


**Figure 6.** Effect of membrane operating pressure on permeate flux performance

Overall, the pressure–flux relationship observed in this study demonstrates that membrane performance is influenced not only by hydraulic driving force but also by concentration polarization and fouling behavior. Within the pressure range investigated, 2-bar provided the most favorable combination of permeate flux and operational stability and was therefore selected for the subsequent continuous filtration and fouling assessment. However, this condition represents the best-performing condition among those experimentally evaluated rather than a statistically validated global optimum. Further studies involving a broader pressure range, replicated experiments, and formal statistical or response-surface optimization are required to determine the true optimum operating pressure. The relationship between operating pressure and membrane flux is illustrated in Figure 6.

3.5.2 Effect of Hydraulic Retention Time on TSS Removal Efficiency

The influence of hydraulic retention time (HRT) in the lamella separator was evaluated at two operational conditions, namely 30 min and 60 min, to determine its effect on suspended solids removal prior to ultrafiltration. The results of the experimental evaluation are presented in Table 5.

**Table 5**. Effect of hydraulic retention time on TSS removal efficiency

| Hydraulic Retention Time (min) | TSS Removal Efficiency (%) |
|---|---|
| 30 | 60 |
| 60 | 75 |

The results show that increasing HRT significantly improved the performance of the lamella separator in removing total suspended solids (TSS). At 30 min HRT, the system achieved a removal efficiency of approximately 60%, while extending the retention time to 60 min increased efficiency to around 75%. This improvement reflects the enhanced settling performance of suspended particles under longer residence time conditions, allowing gravity-driven sedimentation to proceed more effectively within the inclined plate configuration.

This behavior is consistent with the sedimentation principles described by **(BACH & SCHOENBRUNN, 2022)** Liquid–Solid Separation: Sedimentation and Filtration, which emphasizes that increasing detention time in inclined plate settlers enhances particle settling probability by providing sufficient time for discrete and flocculent particles to overcome upward hydraulic drag forces. Similarly, (Zhang et al., 2025) Analysis of settling efficiency and structural optimization of settling tank reported that hydraulic retention time is one of the dominant parameters controlling settling efficiency, where longer retention enhances solid–liquid separation performance until reaching a hydraulic equilibrium condition.

From a mechanistic perspective, the improved TSS removal at longer HRT can be explained by increased particle–plate interaction time and reduced turbulence intensity within the lamella channels. As wastewater remains longer in the settling zone, suspended particles have a higher probability of contacting the inclined surfaces and settling under gravitational forces. This also reduces the concentration of particulate matter entering the downstream ultrafiltration membrane, thereby indirectly contributing to fouling mitigation, as also highlighted in membrane pretreatment studies by (El Batouti et al., 2022) Review of fouling mitigation in membrane separation processes.

However, the results also indicate a practical operational trade-off. While longer HRT improves sedimentation efficiency, it simultaneously leads to increased sludge accumulation at the bottom of the lamella separator. Excessive sludge build-up may reduce effective settling volume, disturb flow distribution, and potentially decrease long-term hydraulic efficiency if not managed properly. This limitation is also reported in gravity-based separation systems, where sediment accumulation becomes a critical operational constraint if sludge withdrawal is not regularly implemented (Bach & Schoenbrunn 2022).

In comparison with integrated wastewater treatment systems reported in previous studies, the obtained TSS removal efficiency of 75% at 60 min HRT is within the effective performance range of lamella-based pretreatment units. For instance, hybrid systems combining sedimentation and membrane filtration reported by (Bedru et al., 2025) Advances in membrane technology for pollutant removal demonstrated that effective pretreatment significantly enhances downstream membrane stability by reducing particulate loading and fouling potential. This aligns with the present study, where improved sedimentation performance directly contributed to lower fouling intensity in the ultrafiltration stage.

Overall, the findings confirm that hydraulic retention time is an important operational parameter influencing the performance of the lamella separator. Increasing the HRT from 30 to 60 min improved TSS removal efficiency from approximately 60% to 75%. Therefore, an HRT of 60 min was identified as the most favorable condition among the two HRT values investigated and was selected for the subsequent integrated treatment assessment. Nevertheless, this result should be interpreted as a comparative finding within the tested experimental range rather than as a definitive optimum HRT. A broader range of HRT values combined with replicated experiments and formal statistical optimization would be necessary to establish the true optimum hydraulic retention time for the system. The effect of hydraulic retention time on TSS removal efficiency is illustrated in Figure 7.

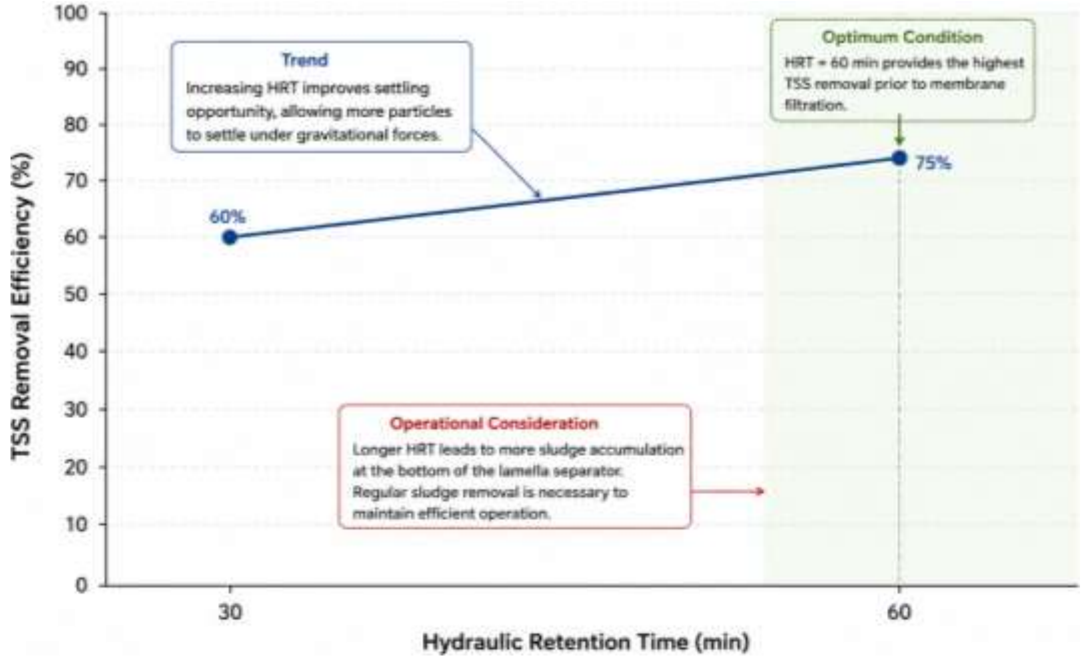


**Figure 7.** Effect of hydraulic retention time on TSS removal efficiency in the lamella separator

### 3.6 Comparison with Previous Studies and Research Implications

The findings of this study are generally consistent with previous research on integrated wastewater treatment systems that combine sedimentation-based pretreatment and membrane filtration technologies. **(**Bach

& Schoenbrunn 2022) emphasize that lamella sedimentation significantly enhances suspended solids removal efficiency by increasing effective settling area and improving particle settling dynamics through inclined plate configurations. In line with this, the present study also demonstrates high removal efficiencies for turbidity and TSS, confirming that lamella separators are highly effective as a first-stage treatment for reducing particulate loading prior to membrane filtration. Similarly, (Li et al., 2023) report that ultrafiltration membranes provide strong rejection of fine suspended particles and contribute substantially to improved effluent quality, particularly in systems treating complex wastewater streams.

However, compared with previous studies, the present research extends the understanding of integrated treatment systems by not only evaluating pollutant removal performance but also systematically analyzing operational behavior, including membrane flux decline, fouling characteristics, flux recovery, and the influence of key operational parameters such as hydraulic retention time (HRT) and transmembrane pressure. This broader evaluation provides a more comprehensive understanding of system performance under realistic operational conditions. The results of (El Batouti et al., 2022) further support the importance of pretreatment in membrane systems, particularly in shifting fouling mechanisms from severe irreversible fouling to more manageable reversible cake layer formation. In this study, such behavior is clearly observed, where flux decline remains controlled and flux recovery after backwashing reaches up to 90%, indicating predominantly reversible fouling mechanisms.

In comparison with alternative pretreatment approaches such as adsorption and chemical coagulation, the integrated lamella separator–ultrafiltration system offers notable operational and environmental advantages. (Skouteris et al., 2015) and (Qalyoubi et al., 2021) highlight that adsorption-based and chemically assisted membrane systems can effectively reduce fouling; however, these methods often introduce secondary challenges such as chemical consumption, sludge generation, and the need for adsorbent regeneration. In contrast, the lamella separator operates through purely physical mechanisms without requiring chemical additives, thereby minimizing secondary waste production and simplifying operational requirements. This makes the system more sustainable and economically attractive for long-term wastewater treatment applications.

Furthermore, the study aligns with (Wang et al., 2020), who demonstrated that effective pretreatment significantly alleviates membrane fouling and stabilizes flux performance in hybrid membrane systems. The present results reinforce this conclusion, showing that reduced suspended solids loading from the lamella separator directly contributes to lower fouling rates and improved hydraulic stability in the ultrafiltration unit. (Bedru et al., 2025) also emphasize that integrated membrane systems perform more efficiently when preceded by effective solid–liquid separation processes, particularly in improving system resilience and operational consistency. The current findings strengthen this argument by demonstrating improved flux stability and reduced fouling intensity under the selected pretreatment and operating conditions investigated in this study. The results indicate that the combination of a 60-min HRT and a 2-bar membrane operating pressure provided favorable performance within the experimental conditions evaluated. However, these conditions should not be regarded as universally optimized, since the experimental design included only two HRT levels and three membrane pressure levels without a formal statistical optimization framework.

From an environmental and practical application perspective, the integrated system demonstrates strong potential for industrial wastewater treatment applications. The substantial reductions in turbidity, TSS, COD, BOD, and heavy metals confirm that the system is capable of producing effluent that meets discharge standards while minimizing environmental impact. In addition, the low chemical dependency and high flux recovery performance enhance its suitability for sustainable implementation. (Mohammed et al., 2024) and (Abbas et al., 2024) also underline the importance of integrated physical–membrane systems in improving pollutant removal efficiency, particularly for complex wastewater containing mixed organic and inorganic contaminants.

From a treatment-performance perspective, the most important organic pollutant result was the reduction in COD, which decreased from 203.318 mg/L in the influent to 42.70 mg/L in the final permeate. This represents a substantial reduction in the pollutant parameter that initially exceeded the discharge limit. The results demonstrate the complementary role of the two treatment stages: the lamella separator removed a considerable fraction of particulate-associated organic matter, while the UF membrane provided additional retention of residual suspended, colloidal, and macromolecular organic constituents. In contrast, the initial BOD concentration was already below the discharge limit, and therefore the observed BOD reduction should be regarded as an additional treatment benefit rather than the primary evidence of treatment necessity. The results further emphasize that COD removal by UF should not be interpreted as complete removal of all dissolved organic compounds, since freely dissolved low-molecular-weight substances may pass through the membrane depending on their molecular size and interactions with other wastewater constituents.

The interpretation of heavy-metal removal in the present study requires particular caution. Although the integrated treatment system produced an approximately 95% reduction in the measured concentrations of Cu, Pb, and Hg, the initial concentrations were already below the applicable discharge limits. Consequently, the practical significance of this reduction is different from that of removing metals from wastewater initially exceeding regulatory standards. Moreover, because the study did not include metal-speciation analysis, the measured reduction cannot be used to distinguish between the removal of particulate-bound metals, colloidal metal species, metal–organic complexes, and truly dissolved ions. The results therefore demonstrate a reduction in measured total metal concentrations under the tested treatment conditions, but do not establish that the UF membrane efficiently removed free dissolved metal ions. Future studies should include dissolved and particulate fractionation, membrane-feed and permeate speciation analysis, and method detection-limit reporting to clarify the mechanisms governing metal transport through the integrated treatment system.

The membrane-only control experiment further strengthened the interpretation of the role of lamella pretreatment in fouling mitigation. Direct ultrafiltration of untreated wastewater resulted in a more pronounced flux decline than the integrated lamella separator–ultrafiltration configuration, demonstrating that the removal of suspended solids before membrane filtration provided a measurable operational benefit. The comparison indicates that the lamella separator did not merely function as an additional pollutant-removal unit but also acted as a fouling-control barrier by reducing the particulate and colloidal loading imposed on the membrane. Therefore, the improved flux stability and high flux recovery observed in the integrated system can be more confidently attributed to the combined treatment configuration. The membrane-only control thus provides an important baseline for evaluating the synergistic effect of physical pretreatment and ultrafiltration.

The current findings strengthen this argument by demonstrating improved short-term flux stability and substantial flux recovery after hydraulic backwashing under the selected experimental conditions. The results suggest that lamella pretreatment can reduce the particulate loading entering the ultrafiltration membrane and consequently contribute to improved short-term fouling control. However, the 8-h experimental duration is insufficient to establish long-term membrane durability, operational lifespan improvement, or sustained performance over repeated cleaning cycles. Therefore, the present findings should be interpreted as evidence of short-term operational benefits rather than definitive proof of extended membrane lifespan.

Accordingly, the regulatory comparison presented in this study should be interpreted with appropriate caution. The wastewater investigated was generated from chemical and biochemical laboratory activities and therefore represents a mixed laboratory wastewater stream rather than wastewater from a single standardized industrial sector. The reported comparison with Indonesian discharge criteria is intended to provide an environmental-performance benchmark for the treatment system. It does not imply that the selected numerical limits constitute a universally applicable discharge standard specifically established for all laboratory wastewater under PP No. 22/2021. For practical regulatory compliance, the final discharge requirements must be verified against the specific classification of the facility and the requirements stated in its applicable environmental approval and technical approval.

The regulatory comparison also requires distinction between environmental water-quality classes and wastewater discharge standards. The values used for comparison in this study were therefore treated as regulatory benchmarks for evaluating the environmental performance of the treatment process, rather than as a universal discharge standard specifically applicable to all laboratory wastewater. Since laboratory wastewater may vary substantially depending on the chemicals, biological materials, analytical procedures, and facility activities involved, the applicable discharge requirements should ultimately be determined according to the specific activity classification and environmental authorization of the generating facility. This distinction is particularly important when interpreting parameters such as COD, BOD, TSS, turbidity, and heavy metals, because compliance with a selected benchmark does not necessarily establish regulatory compliance in the absence of confirmation of the legally applicable category for the specific facility.

Overall, the results of this study confirm that optimizing lamella separator pretreatment plays a critical role in enhancing ultrafiltration membrane performance. By effectively reducing suspended pollutant loads prior to membrane filtration, the system successfully minimizes fouling intensity, improves flux stability, and extends operational sustainability. In addition, the synergy between sedimentation and membrane processes provides a robust and environmentally friendly approach to wastewater treatment. These findings contribute to the growing body of knowledge on hybrid treatment systems and support the development of more efficient, low-chemical, and sustainable wastewater treatment technologies for industrial applications.

### 3.7 Study Limitations and Future Perspectives

Despite the encouraging performance of the integrated lamella separator–ultrafiltration system, several limitations need to be acknowledged in interpreting the findings of this study. First, the experimental work was conducted at laboratory scale under relatively stable and controlled operating conditions. While this approach is suitable for evaluating fundamental process performance and optimization of operational parameters, it does not fully represent the variability encountered in real industrial wastewater systems. In practical applications, wastewater characteristics often fluctuate due to changes in production processes, seasonal variations, and operational disruptions. Therefore, pilot-scale and full-scale studies are required to validate the robustness and scalability of the proposed system under real operational conditions.

Another limitation concerns the relatively narrow range of operational conditions investigated for process optimization. The effects of only two hydraulic retention times (30 and 60 min) and three transmembrane pressures (1, 2, and 3 bar) were evaluated. Although these experiments enabled a comparative assessment of the influence of HRT and operating pressure, the experimental design was not sufficiently broad to establish a statistically validated global optimum. In addition, formal statistical analyses such as analysis of variance (ANOVA), response-surface methodology, or other multivariable optimization approaches were not applied. Therefore, the operating conditions identified in this study should be interpreted as favorable conditions within the tested experimental range rather than definitive optimum conditions. Future studies should employ a broader experimental design with independent replicates and appropriate statistical analysis to quantify the significance of individual operational factors and their interactions and to establish statistically robust optimum operating conditions.

Second, the scope of water quality parameters analyzed in this study was limited to key indicators such as TSS, turbidity, COD, BOD, and selected heavy metals (Cu, Pb, and Hg). Although these parameters provide a strong baseline for evaluating general treatment performance, they do not fully represent the complexity of industrial wastewater. Emerging contaminants such as pharmaceutical residues, surfactants, microplastics, nutrients (nitrogen and phosphorus compounds), and pathogenic microorganisms were not included in the analysis. Previous studies such as (Mohammed et al., 2024) and (Abbas et al., 2024) highlight that modern industrial wastewater often contains a broader range of micropollutants that require advanced analytical and treatment approaches. Therefore, future research should expand the spectrum of monitored pollutants to provide a more comprehensive assessment of treatment effectiveness and environmental safety.

Third, although membrane performance was evaluated in terms of flux decline, fouling development, and flux recovery after backwashing, the study did not include detailed fouling mechanism characterization. Advanced analytical techniques such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), energy dispersive X-ray (EDX) analysis, or resistance-in-series modeling were not applied. These techniques, as discussed in (El Batouti et al., 2022), are essential for identifying the specific nature of fouling layers, distinguishing between organic, inorganic, and biofouling components, and understanding irreversible fouling mechanisms. The absence of such analyses limits the depth of mechanistic interpretation of membrane fouling behavior in this study.

In addition, the economic feasibility and life-cycle assessment of the integrated system were not evaluated. Operational costs, energy consumption, sludge handling, and membrane replacement frequency are important factors that determine the practical applicability of wastewater treatment technologies at industrial scale. Studies such as (Skouteris et al., 2015) and (Wang et al., 2020) emphasize that economic and operational sustainability are critical considerations in the adoption of membrane-based treatment systems. Therefore, future research should incorporate techno-economic analysis and life-cycle assessment to evaluate the cost-effectiveness and sustainability of the proposed system.

A further limitation concerns the duration and depth of the membrane fouling assessment. The membrane filtration experiment was conducted for 8 h, which was sufficient to observe short-term flux decline and evaluate the effectiveness of hydraulic backwashing but was insufficient to assess long-term membrane durability, irreversible fouling accumulation, membrane aging, or actual membrane lifespan. In addition, the fouling analysis was based primarily on permeate flux decline and flux recovery, while a quantitative resistance-in-series analysis was not performed. Consequently, the individual contributions of membrane resistance, cake-layer resistance, concentration polarization, and irreversible fouling could not be separately quantified. Future studies should include longer-duration filtration experiments, repeated filtration and cleaning cycles, clean-water permeability measurements, resistance-in-series modeling, and direct characterization of the fouling layer using techniques such as SEM, FTIR, and EDX. These approaches would provide a more comprehensive understanding of fouling mechanisms and enable a more reliable assessment of long-term membrane durability and lifespan.

Furthermore, while the current study demonstrates the effectiveness of lamella pretreatment in reducing fouling and improving membrane performance, additional optimization involving hybrid treatment configurations could be explored. Integration with coagulation–flocculation, adsorption processes, or advanced oxidation processes (AOPs) may further enhance the removal of dissolved organic pollutants and micropollutants that are less responsive to sedimentation and ultrafiltration alone. (Bedru et al., 2025) and (Li et al., 2023) highlight that hybrid treatment systems can significantly improve overall removal efficiency and operational stability by combining complementary mechanisms.

Overall, future research should focus on scaling up the system, expanding pollutant coverage, improving fouling characterization, and integrating economic and environmental assessments. Such comprehensive investigations will strengthen the scientific and practical foundation of integrated lamella separator–membrane systems, enabling their wider application in sustainable industrial wastewater treatment and environmental protection strategies.

## 4. CONCLUSIONS

This study demonstrates that the integration of an optimized lamella separator as a pretreatment unit with an ultrafiltration membrane system significantly enhances the treatment performance of industrial laboratory wastewater. The lamella separator effectively reduces suspended solids and turbidity, thereby lowering the pollutant loading entering the membrane system and contributing to improved overall removal efficiencies. Subsequent ultrafiltration further enhances effluent quality, achieving high reductions in TSS, COD, BOD, turbidity, and heavy metals, resulting in treated water that meets discharge standards. In addition, the integrated system shows improved operational stability, with predominantly reversible membrane fouling and effective flux recovery through backwashing, confirming the synergistic role of pretreatment in maintaining membrane performance and reducing fouling intensity.

The treated wastewater achieved concentrations below the selected Indonesian regulatory benchmark values used for comparison in this study. However, because the applicable discharge requirements for laboratory wastewater depend on the specific classification of the generating activity and its environmental authorization, these results should be interpreted as an indication of treatment performance relative to the selected benchmarks rather than as a definitive determination of regulatory compliance for all laboratory wastewater.

Subsequent ultrafiltration further enhanced effluent quality, particularly through the substantial reduction of turbidity, TSS, and COD. The integrated system reduced COD from 203.318 mg/L to 42.70 mg/L, while turbidity and TSS removal reached approximately 98% and 98.8%, respectively. These results demonstrate the complementary role of lamella sedimentation and ultrafiltration in removing particulate, colloidal, and selected macromolecular pollutant fractions. Although BOD was also substantially reduced, its initial concentration was already below the applicable discharge limit; therefore, BOD reduction represents an additional treatment benefit rather than the principal treatment requirement. The membrane system also demonstrated favorable short-term fouling control, with approximately 90% flux recovery after hydraulic backwashing.

Subsequent ultrafiltration further enhanced effluent quality by substantially reducing TSS, turbidity, COD, BOD, and the measured concentrations of Cu, Pb, and Hg. However, the reduction in heavy-metal concentrations should be interpreted as a decrease in measured total concentrations rather than as direct evidence of efficient rejection of truly dissolved and uncomplexed metal ions, because metal speciation was not determined in this study. The observed metal reduction was likely associated primarily with the removal of particulate, colloidal, and complexed metal fractions during the combined sedimentation and membrane treatment processes.

Within the experimental ranges investigated, the combination of a 60-min hydraulic retention time and a 2-bar transmembrane pressure provided the most favorable treatment and membrane performance. However, these conditions represent the best-performing conditions among those tested and should not be interpreted as universally optimized operating conditions. Further research involving a broader experimental design, independent replicates, and formal statistical optimization is required to establish statistically validated optimum operating conditions.

The integrated system also demonstrated favorable short-term membrane operational performance. Although the permeate flux decreased during the 8-h filtration period, approximately 90% of the initial flux was recovered after hydraulic backwashing, indicating that a substantial proportion of the observed fouling was reversible. These findings demonstrate the short-term effectiveness of lamella pretreatment in reducing particulate loading and supporting membrane fouling control. However, the present study does not establish long-term membrane lifespan improvement, and further extended-duration experiments, repeated cleaning cycles, and quantitative resistance analysis are required to evaluate membrane durability and long-term operational sustainability.

Based on these findings, it is recommended that future applications of membrane-based wastewater treatment systems prioritize the incorporation of efficient physical pretreatment units such as lamella separators to improve sustainability and reduce operational costs. Further research should focus on pilot- and full-scale implementation to evaluate long-term performance under real industrial conditions, including fluctuating influent characteristics. In addition, more advanced fouling characterization techniques and economic assessments are needed to optimize system design and operational strategies. The integration of hybrid processes such as coagulation, adsorption, or advanced oxidation is also recommended to further enhance pollutant removal efficiency and ensure broader applicability in complex wastewater treatment scenarios.

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