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POTENTIAL REUSE OF WASTEWATER BY UTILIZING NANO-FILTRATION TECHNIQUE-A RESEARCH PAPER

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Abstract
The generation of wastewater from human activities is an inevitable consequence of urbanization and industrialization. In Pakistan, where water scarcity is exacerbated by aging infrastructure and increasing demand, the development of cost-effective and efficient water treatment technologies is crucial. Conventional wastewater treatment plants (CWWTPs) are often limited by high construction and maintenance costs, as well as significant land requirements. This study evaluates the performance of nanofiltration (NF) membranes for wastewater treatment as a sustainable alternative. A pilot-scale NF system using hollow fiber membranes with a pore size of 0.002 µm was employed to assess the removal efficiency of key water quality parameters, including biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), turbidity, hardness, and pH. Experiments were conducted at pressures ranging from 4 to 10 bars, with optimal performance observed at a filtration time of 15–20 minutes and a flux rate of 20 L/m²·h using undiluted wastewater. Results indicated a marked improvement in treatment efficiency with increasing operating pressure, demonstrating the potential of direct NF treatment in reducing contaminants effectively while minimizing infrastructure demands.

INTRODUCTION

Water Pollution

Water is a vital natural resource, essential for sustaining life, agriculture, and industrial development(Jhariya, Banerjee, & Meena, 2022). However, rapid industrialization and urban expansion, though beneficial in many aspects, have brought with them significant environmental challenges—foremost among them being water pollution. The problem arises when waste materials discharged into water bodies exceed their natural capacity to assimilate and neutralize contaminants, resulting in the degradation of water quality(Akhtar, Syakir Ishak, Bhawani, & Umar, 2021). Polluted water can harbor toxic substances that persist in the environment, posing long-term threats to both human health and ecological systems(Madhav et al., 2020).

Human activity is the primary contributor to water pollution, whether through point sources—such as wastewater discharge from industrial plants, sewage treatment facilities, and other identifiable outlets—or non-point sources, which include diffuse runoff from agricultural fields, urban landscapes, and mining sites(Xiao & Ji, 2007). These latter sources are particularly difficult to manage because they cannot be traced back to a specific discharge point. Fertilizers, pesticides, sediments, and organic wastes from such sources enter water bodies and can contaminate surface and groundwater alike(Ritter, 2002). Agricultural runoff, for instance, frequently carries high levels of phosphates and nitrates, which promote the excessive growth of algae in aquatic environments—a phenomenon known as eutrophication. This leads to oxygen depletion, foul odors, and the proliferation of harmful microorganisms(Aung & Kyi, 2018).

In addition to nutrient pollution, water bodies are increasingly contaminated with radioactive substances, heavy metals, and synthetic organic chemicals(Madhav et al., 2020). Wastewater from hospitals, industrial zones, and uranium mines may contain hazardous isotopes such as radon, while chemical effluents may include substances like phenols, polychlorinated biphenyls (PCBs), and benzene. These pollutants, often carcinogenic or mutagenic, are not easily degraded and can remain active in the environment for long periods. Mitigating such contamination requires proactive measures, including stringent wastewater treatment protocols, public education on the disposal of household chemicals, and industrial compliance with environmental regulations(Khan, Ahmad, Manzoor, & Khan, 2010). Community engagement is essential for promoting safe disposal practices and reducing the environmental burden on freshwater resources(Dubrow et al., 2010).

Wastewater and Its Characteristics

Wastewater refers to any water that has been adversely affected in quality by anthropogenic influences(Akhtar et al., 2021). It originates from domestic households, commercial establishments, industrial processes, and agricultural activities. Urban wastewater is particularly complex due to the mixing of effluents from multiple sources, resulting in a cocktail of physical, chemical, and biological contaminants. The safe and effective treatment of wastewater is crucial not only for human health but also for environmental sustainability(Obaideen et al., 2022).

Physically, wastewater is characterized by its total solids content, which includes both suspended and dissolved particles(Henze & Comeau, 2008). Parameters such as color, temperature, odor, and turbidity also play a significant role in assessing water quality. Suspended solids, especially in industrial wastewater, can be abundant and are typically removed through screening and sedimentation during the initial treatment stages. These solids, when not treated properly, can clog pipelines, reduce the efficiency of biological treatment systems, and cause aesthetic and ecological problems when discharged into the environment(Sravya, Sowmika, Anjum, & Golla, 2025).

Chemically, wastewater contains both organic and inorganic compounds. Organic matter typically includes carbon-based substances such as proteins, fats, carbohydrates, and more complex synthetic chemicals found in detergents, pesticides, and industrial solvents(Egbedina, Bolade, Ewuzie, & Lima, 2022). These compounds are often biologically degradable but can also include persistent organic pollutants that resist conventional treatment methods. Two key indicators of organic pollution are Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)(Lv et al., 2024). BOD measures the amount of dissolved oxygen required by aerobic biological organisms to break down organic material, while COD provides a broader estimate of the amount of oxygen needed to chemically oxidize all organic matter in the sample. COD testing, unlike BOD, can be performed more quickly and is useful for rapid assessment of water treatment performance(Zulyadaini)

Inorganic pollutants in wastewater include nutrients such as nitrogen and phosphorus, as well as heavy metals like chromium, mercury, cadmium, and lead. These substances can originate from a wide range of industrial processes and, in excessive concentrations, pose serious threats to aquatic life and human health. The pH of wastewater is also a critical parameter, as most biological treatment systems operate optimally within a narrow pH range. Acidic or highly alkaline wastewater can disrupt treatment processes and damage infrastructure (Barber, 2011).The presence of heavy metals is particularly concerning due to their toxicity, persistence, and bioaccumulation in the food chain. For instance, chromium compounds are especially harmful to plant and microbial life, affecting growth and metabolic functions(Mishra & Tripathi, 2008).

Public Health Implications of Wastewater

The improper handling and discharge of untreated or partially treated wastewater can lead to the spread of numerous diseases. Pathogens present in wastewater—including bacteria, viruses, and protozoa—can infect humans through direct contact, ingestion of contaminated water or food, or through vectors such as flies and mosquitoes. These organisms are responsible for a range of illnesses, including typhoid, cholera, dysentery, and various gastrointestinal infections(Kotowska, Żalikowski, & Isidorov, 2012). Symptoms often include fever, diarrhea, vomiting, abdominal cramps, and dehydration, which in severe cases can lead to death, especially among vulnerable populations like children and the elderly(Domachowske & Dennehy). Eutrophication caused by nutrient overloads can further exacerbate public health concerns. Algal blooms not only deplete oxygen levels in water bodies, leading to fish kills, but also release toxins that contaminate drinking water supplies(Demeke & Tassew, 2016). Excessive nitrogen in water has been linked to methemoglobinemia or "blue baby syndrome," a potentially fatal condition that impairs the oxygen-carrying capacity of blood in infants. Moreover, long-term exposure to contaminated water is associated with reproductive issues and increased risk of miscarriages (Hrkach et al., 2012).

This research aims to contribute to the development of low-cost, high-efficiency water treatment technologies suitable for countries like Pakistan, where existing infrastructure is insufficient to meet rising demand and environmental safety standards(Nizam et al., 2020).

2. Materials and Methods

2.1 Scope of the Study

This chapter outlines the experimental design, pilot-scale plant setup, sampling methods, and analytical procedures employed to evaluate the performance of a nanofiltration (NF) system using biologically treated wastewater. It covers plant operation, membrane specifications, cleaning procedures, and water quality testing for performance evaluation.

2.2 Study Area

The study was conducted at the **I-9 Sewage Treatment Plant (STP)**, located in Islamabad. This plant treats municipal wastewater through a sequence of physical, chemical, and biological processes. Established in 1964, and upgraded in 2005 to include four operational phases, the I-9 STP employs the **activated sludge process (ASP)** to oxidize organic matter, remove nitrogenous compounds, and reduce phosphate levels. The process consists of screening, sedimentation, aeration, and clarification stages, followed by effluent discharge into the Swan Stream.

2.3 Experimental Setup

2.3.1 Pilot-Scale NF Treatment System

A pilot-scale nanofiltration unit was constructed, comprising:

- **Feed Tank** (PVC, 230 L capacity)
- **Multistage Pump** (3 HP, 5 impellers; pressure range: 2–6 bar)
- **NF Membrane** (spiral-wound, cellulose acetate; pore size: 0.002 µm; 4"x40")
- **Flow Meter** (digital, m^3/h)
- **Pressure Gauge** (dual unit: bar/psi)
- **Pressure Regulator** (for pressure modulation)
- **Iron piping and control valves**

2.3.2 Wastewater Source

The NF system used effluent from I-9 STP as feedwater. This biologically treated wastewater originated from various Islamabad sectors and newly developed housing colonies, comprising both domestic and commercial discharges.

2.3.3 Schematic Diagram

A flow schematic of the NF system was developed to illustrate the arrangement of major components (refer to attached figures in the annexure).

2.4 Transmembrane Pressure (TMP)

Transmembrane pressure, the driving force behind membrane filtration, was maintained within the range of **75–150 psi**, depending on the operational cycle. The system required membrane cleaning every ~15 days of operation to manage fouling and maintain TMP efficiency.

2.5 Membrane Cleaning

2.5.1 Chemical Cleaning

Flocon 135, a phosphine carboxylic acid-based antiscalant, was used for chemical cleaning to prevent inorganic scale formation (e.g., $CaCO_3$, $CaSO_4$). Cleaning was performed every two months, for approximately two minutes, to restore membrane performance.

2.5.2 Backwashing

Backwashing involved reversing the flow (in-to-out) using clean water to dislodge particulate matter from the membrane pores and restore permeability.

2.6 Membrane Fouling

2.6.1 Foulants

Foulants identified included dissolved solids, colloidal matter, polyvalent ions, organic macromolecules, and microbial biomass. These caused an estimated **15% reduction in permeate flow** and **10% increase in pressure**.

2.6.2 Fouling Mechanisms

Mechanisms included:

- Precipitation of insoluble salts
- Adsorption of organics
- Bacterial colonization (biofouling)
- Polymer–solute interactions

2.7 Cleaning Agents and Protocols

Cleaning protocols varied with membrane characteristics. A combination of alkaline cleaners and oxidants was used depending on foulant type. Cleaning efficiency was evaluated through performance recovery indicators such as permeability, pressure drop, and visual clarity of permeate. Cleaning was followed by flushing with deionized water to remove residual chemicals.

2.8 Cost Considerations

Cost analysis for NF operation included:

- Membrane modules (20–30% of capital cost)
- Energy consumption (dependent on flow rate and pressure)
- Cleaning chemicals and maintenance
- Operational scale effects (larger systems yielded better cost-efficiency) Pilot-scale cost data were extrapolated to estimate feasibility for full-scale deployment.

2.9 Sampling Methods

Water samples were collected at both **inlet and outlet** of the NF system at four pressure levels: **3, 4, 5, and 6 bar**. Each sampling session involved collecting uniform volume samples, which were composited before analysis. A 15-minute stabilization period was observed before sample collection at each pressure setting.

2.10 Experimental Analysis

2.10.1 Parameters Analyzed

Standard methods were used to test the following water quality parameters are Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Hardness, Calcium, Magnesium, Potassium, Chlorides, Sulphates, Salinity and Electrical Conductivity (EC). Tests were performed on permeate samples collected at each operational pressure to evaluate the **removal efficiency** and **performance consistency** of the NF membrane.

3. Results

3.1 Scope

Each water quality parameter was analyzed at varying operational pressures (3–6 bar) to assess the removal efficiency of the nanofiltration (NF) membrane system installed at the pilot scale.

3.2 Solids Analysis

3.2.1 Total Dissolved Solids (TDS)

TDS concentrations in the influent ranged between 850–910 mg/L across three samples. Significant reductions were observed with increasing pressure. For instance, at 6 bar, TDS dropped to as low as 330–360 mg/L. This trend demonstrates improved solute rejection with higher transmembrane pressure, likely due to greater driving force across the NF membrane.

Maximum removal efficiency reached over 61% at 6 bar.

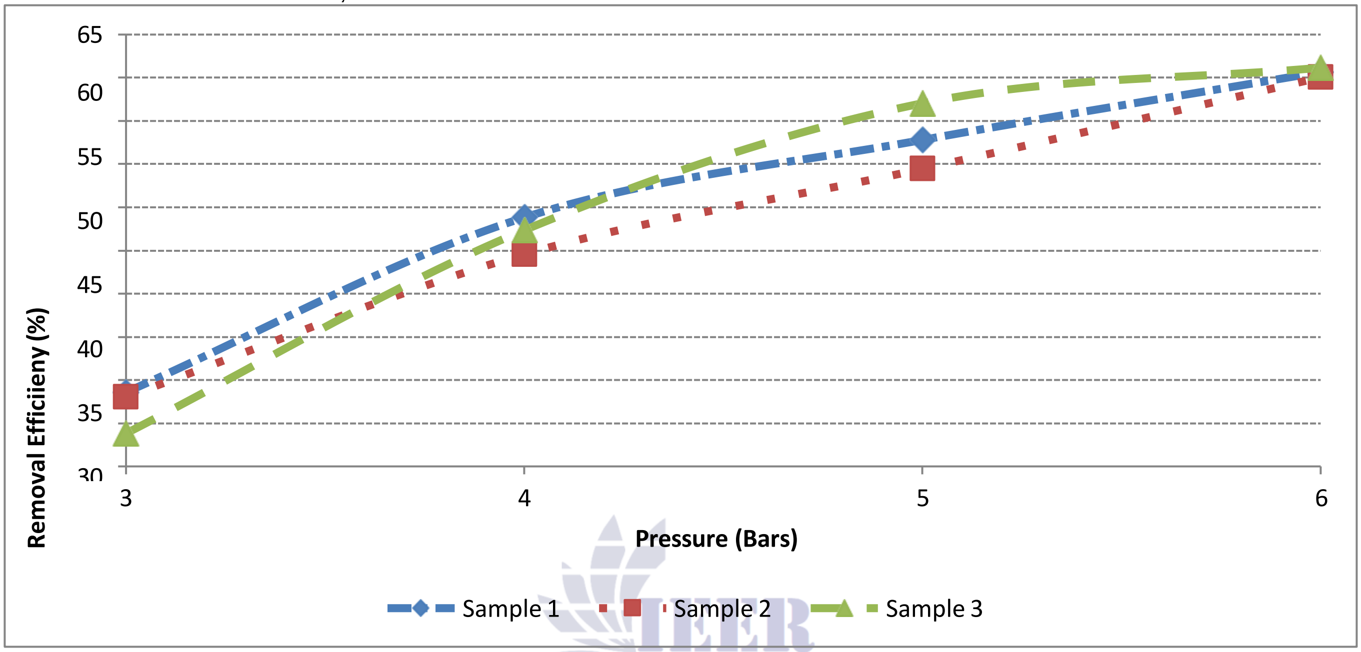


Figure 3.1: The illustration of the progressive TDS removal across all pressure levels.

3.2.2 Total Suspended Solids (TSS)

TSS values also exhibited a sharp decline with rising pressure. Influent concentrations ranged from 245–320 mg/L, while effluent values decreased to as low as 16 mg/L at 6 bar. The NF membrane effectively retained suspended matter, achieving a **removal efficiency of up to 93.46%**, indicating excellent turbidity control.

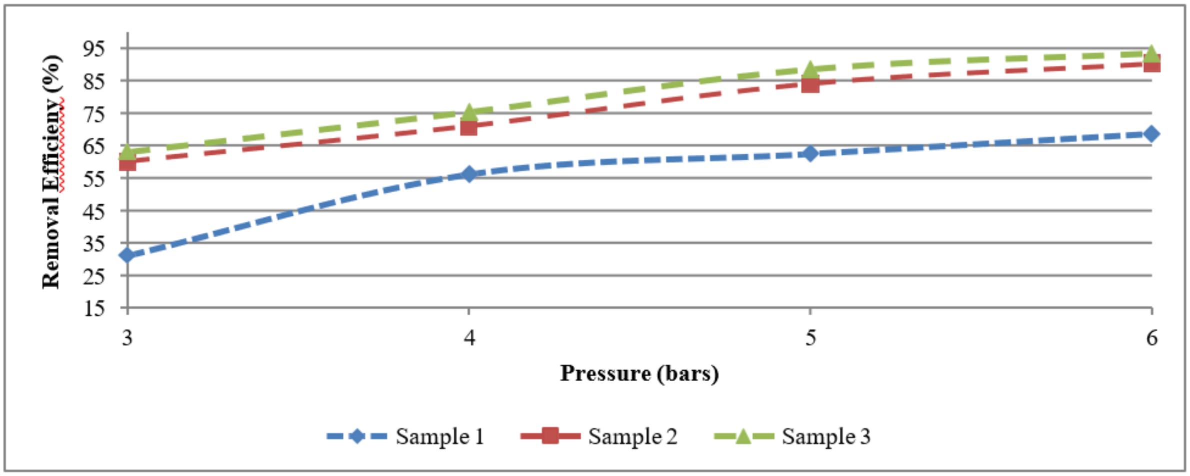


Figure 3.2. TSS as a Function of Pressure

3.3 Organic Pollutants

3.3.1 Biological Oxygen Demand (BOD)

BOD in raw samples ranged from 68–74 mg/L. At 6 bar, BOD was reduced to 3.94–5.1 mg/L, achieving **over 94% removal** in some samples. This high efficiency confirms the NF membrane's potential for reducing biodegradable organic pollutants and improving effluent quality for reuse.

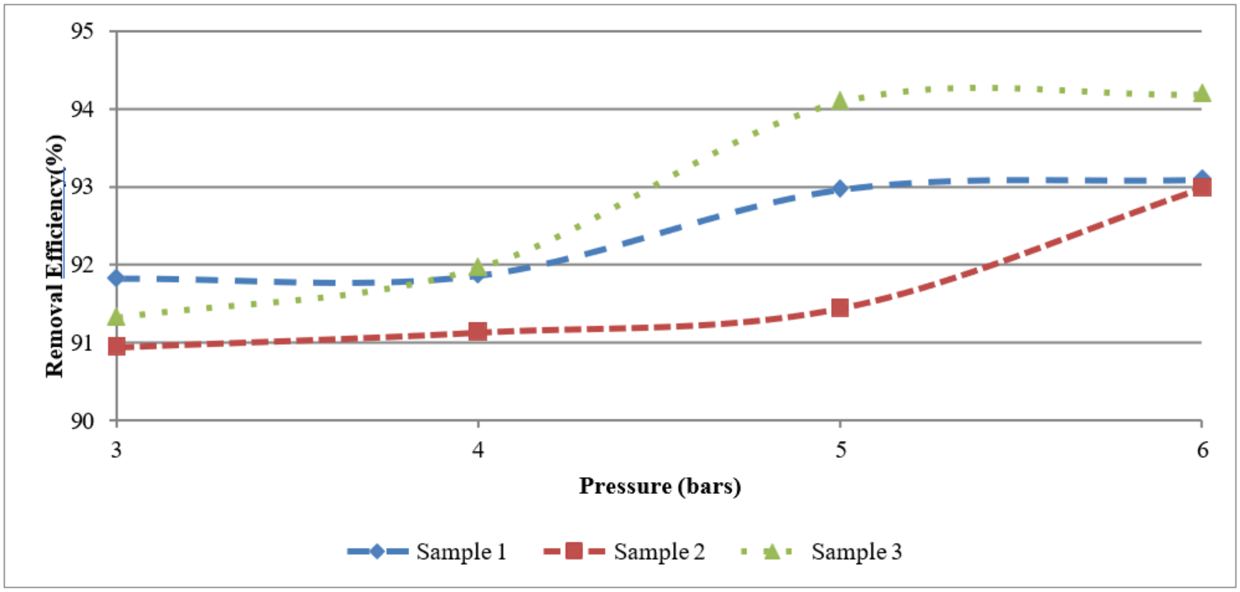


Figure 3.3: BOD as a pressure of function

3.3.2 Chemical Oxygen Demand (COD)

Influent COD values were between 102–118 mg/L. The NF system achieved **COD reductions of up to 36.27%** at 6 bar. Although COD removal was lower than BOD, the consistent decline in values across increasing pressure demonstrates the membrane's role in partially removing non-biodegradable organic content.

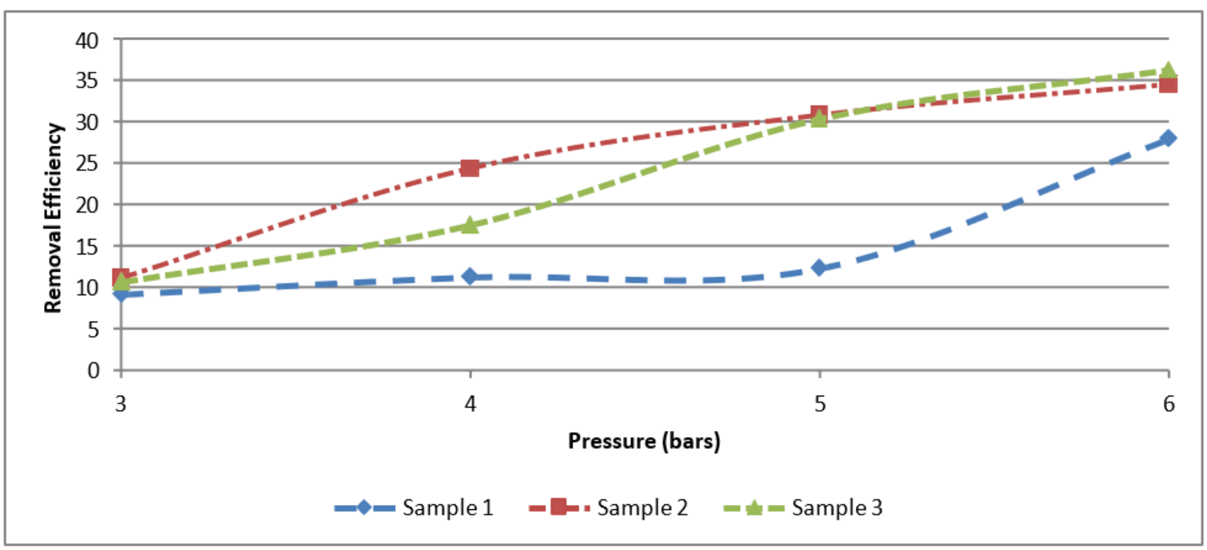
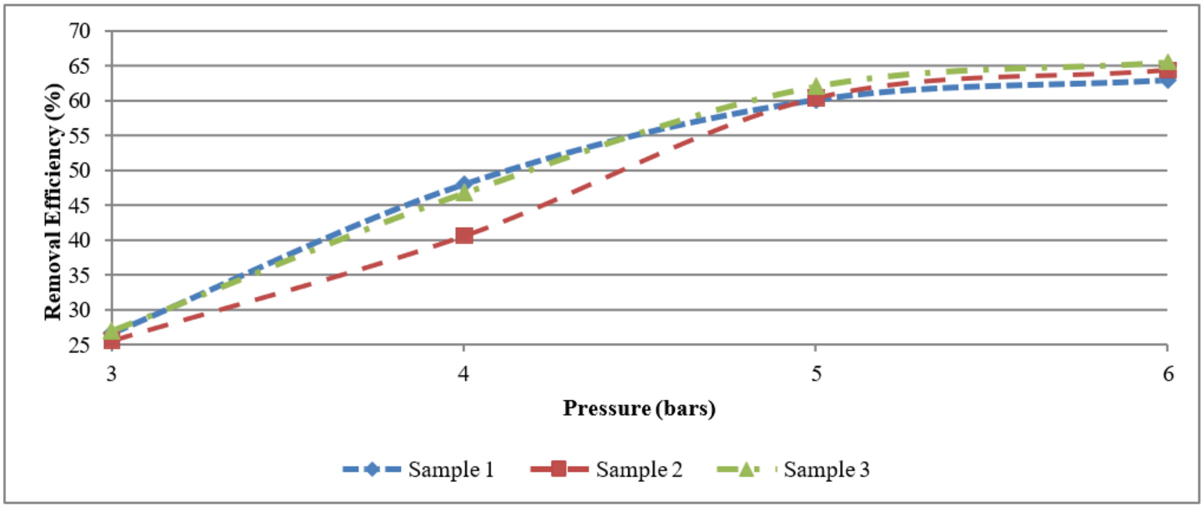


Figure 3.4: COD as a pressure of function

3.4 Inorganic Parameters

3.4.1 Total Hardness

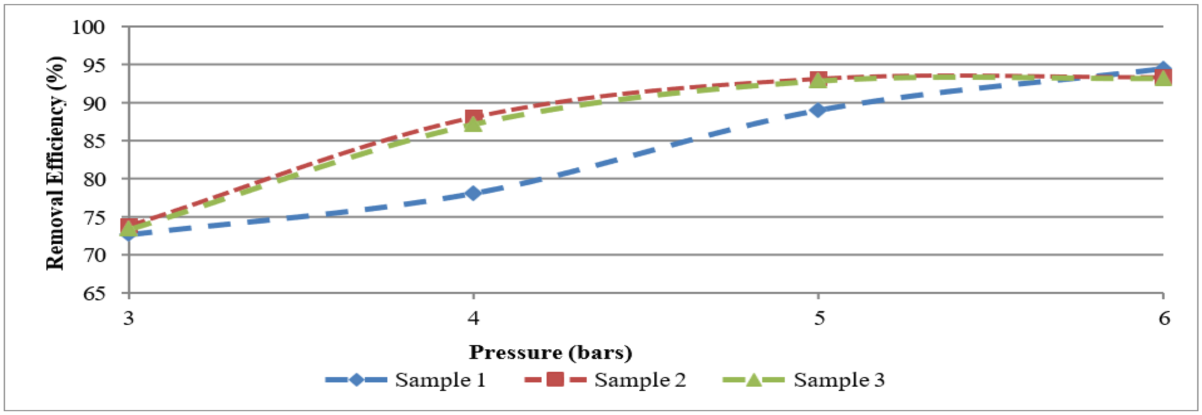
The initial hardness (as $CaCO_3$) varied from 248–281 mg/L. At 6 bar, effluent hardness dropped to 82–104 mg/L. The removal efficiencies ranged from **62.98% to 65.57%**, indicating significant divalent ion rejection capability of the NF membrane, particularly calcium and magnesium.



3.5. Hardness as a function of pressure.

3.4.2 Chlorides

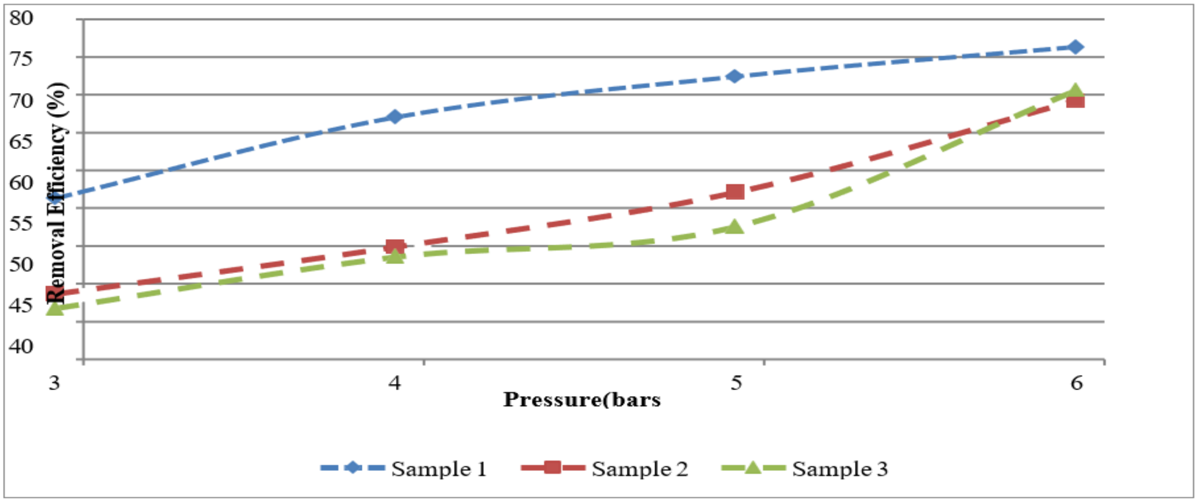
Chloride concentrations were reduced from 47–60 mg/L to approximately 2.91–3.27 mg/L at the highest pressure. With **removal efficiencies exceeding 94%**, NF proved highly effective against monovalent ions, particularly at 6 bar pressure.



3.5. Chlorides as a function of pressure

3.4.3 Sulphates

Sulphate values in the influent (277–330 mg/L) showed considerable reduction in the effluent (82–103 mg/L) at 6 bar, achieving **maximum removal of 76.07%**. This supports the NF membrane's ability to filter multivalent anions effectively.

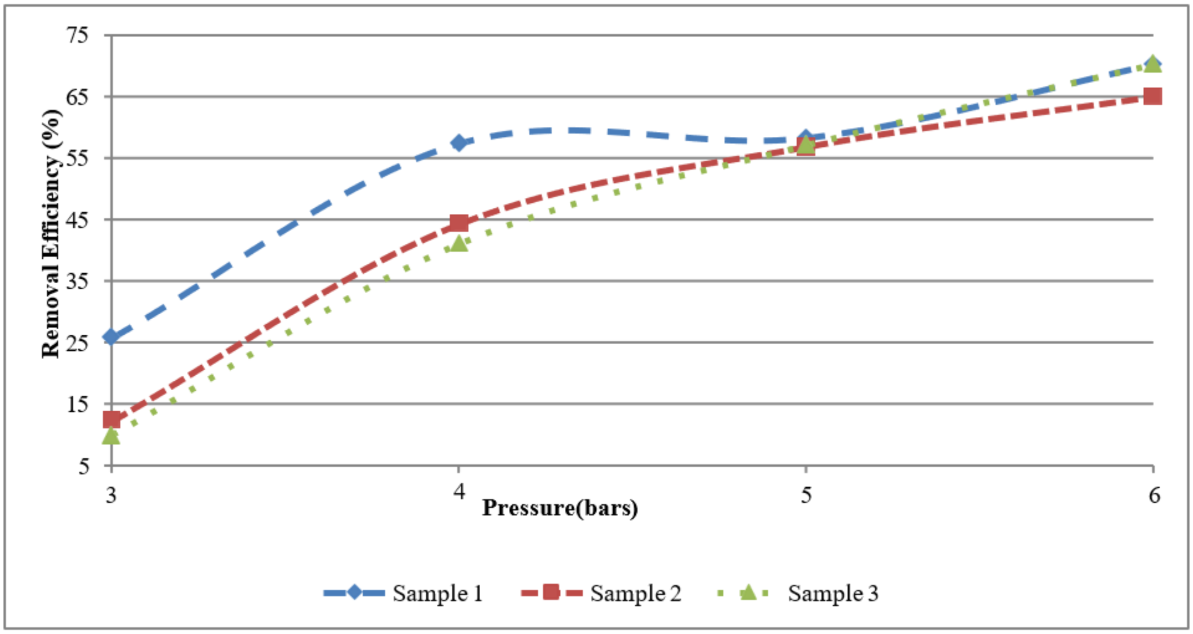


3.6. Sulphates as a function of pressure

3.5 Turbidity and Salinity

3.5.1 Turbidity

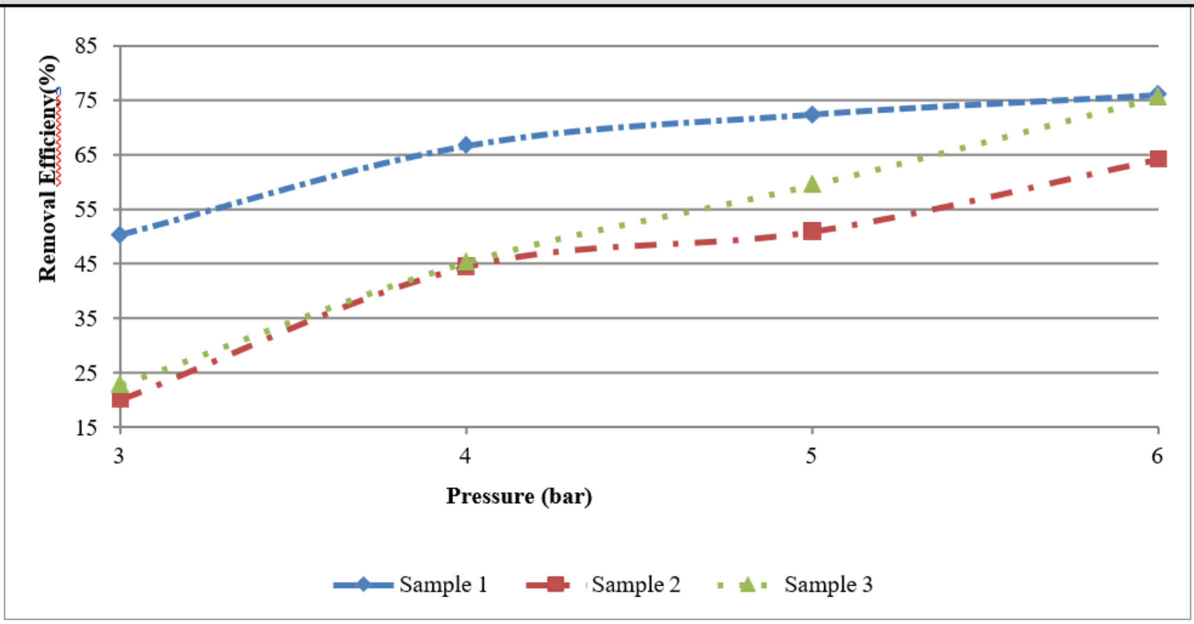
Turbidity levels were greatly improved post-treatment, dropping from up to 8.43 NTU to as low as 2.30 NTU. With **removal efficiencies above 70%**, NF treatment met the **WHO standard** for potable water turbidity.



3.7. Turbidity as a function of pressure

3.5.2 Salinity

Salinity reductions ranged from 50–75% across samples. At 6 bar, salinity dropped from initial values of ~72–79 mg/L to 17–26 mg/L. NF performance in salinity reduction confirmed its effectiveness for water softening and partial desalination.



3.8. Salinity as a function of pressure

3.6 Trace Elements and Heavy Metals

Trace metals commonly present in domestic and commercial effluents—such as aluminum, arsenic, cadmium, chromium, manganese, and copper—were significantly reduced by NF treatment. For instance, aluminum was reduced from 20 mg/L to 4.3 mg/L, and cadmium from 10 mg/L to 0.03 mg/L, indicating strong retention capabilities for hazardous elements.

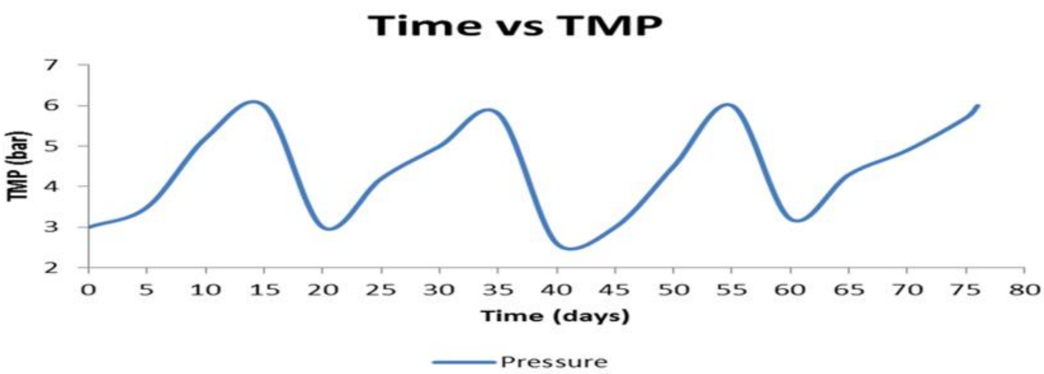
3.7 pH Levels

pH values across influent and effluent samples remained within the acceptable range of 6.5 to 8.4. No significant shifts were observed, confirming that NF treatment had negligible impact on the pH of treated water.

3.8 Membrane Performance and Maintenance

3.8.1 Transmembrane Pressure (TMP)

TMP increased progressively over time due to membrane fouling, with maximum pressure reached after 15 days of operation. Regular monitoring was necessary to maintain system efficiency.



3.9. **Transmembrane Pressure (TMP) as a function of pressure**

3.8.2 Backwashing
Backwashing was performed every 15 days to restore membrane performance. Each session lasted about 2 minutes and successfully alleviated membrane clogging due to accumulated solids.

DISCUSSION
The present study aimed to evaluate the potential of nanofiltration (NF) as a treatment method for wastewater reuse, with a particular focus on how varying pressures influence its efficiency(Mohammad et al., 2015). The experimental findings, based on parameters such as Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Hardness, Chlorides, Sulphates, Turbidity, and Salinity, showed that nanofiltration had a significant impact on improving water quality. As pressure increased, the effectiveness of contaminant removal improved, confirming that pressure is a critical factor in optimizing NF performance(Al-Amoudi & Lovitt, 2007).
The reduction in TDS, TSS, and BOD indicates that NF membranes effectively separate both organic and inorganic pollutants(Ritchie & Bhattacharyya, 2002). This positions NF as a valuable pre-treatment or polishing step in water reuse applications. Additionally, the study observed that although higher pressures enhanced removal efficiency, the volume of permeate (treated water) gradually declined over time due to membrane fouling. This fouling results from the accumulation of particulates and other substances that block membrane pores. Interestingly, this clogging can lead to a reduced effective pore size, which may further enhance contaminant retention, albeit at the cost of decreased flow rate(Jeong, Jun, Cheon, & Park, 2018).
The reuse of treated wastewater, as demonstrated in this study, offers numerous benefits in agricultural, industrial, and urban contexts(Jaramillo & Restrepo, 2017). The use of reclaimed water for irrigation, landscaping, aquaculture, and non-potable industrial processes not only conserves freshwater resources but also promotes environmental sustainability. In areas facing water scarcity, such as many regions in Pakistan, NF-treated wastewater provides an alternative water source, thus improving per capita water availability and reducing pressure on existing freshwater systems(Kashif, 2013).
Furthermore, the treated water complied with the National Environmental Quality Standards (NEQs) for municipal and industrial effluents, reinforcing the suitability of nanofiltration for reuse purposes(Joseph, Al-Hazmi, Śniatała, Esmaeili, & Habibzadeh, 2023). The treated samples met all key parameters, with TDS reduced from 3500 mg/L to 330 mg/L, BOD from 80 mg/L to 3.94 mg/L, and COD from 150 mg/L to 65 mg/L, among others. This underscores the effectiveness of NF membranes in transforming highly contaminated wastewater into a safe and reusable resource(Yadav, Karki, & Ingole, 2022).
However, despite its high performance, the application of NF technology faces limitations primarily due to the high operational costs and membrane fouling(Asif & Zhang, 2021). These challenges hinder widespread adoption, especially in low-resource settings. Long-term viability would require strategies to reduce membrane fouling and associated maintenance costs, such as incorporating pre-treatment steps, using anti-fouling coatings, or employing periodic backwashing techniques(Gkotsis, Banti, Peleka, Zouboulis, & Samaras, 2014).

RECOMMENDATIONS
Based on the findings of this study, several recommendations can be made:

Optimization of Operating Conditions: Pressure levels should be carefully optimized to balance between enhanced contaminant removal and sustainable permeate flow rates.

Implementation in Water-Scarce Areas:
Nanofiltration units should be prioritized in regions facing acute water shortages, especially for agricultural and non-potable industrial applications.

Cost Reduction Strategies: Further research should focus on reducing operational and maintenance costs through innovative materials, automation, and energy-efficient designs.

Membrane Fouling Management: To improve the lifespan and efficiency of NF membranes, pre-treatment protocols and regular cleaning schedules should be integrated into system operations.

Public and Industrial Awareness: Awareness campaigns should be launched to educate communities and industries on the benefits and safe uses of reclaimed water.

Policy Integration: Government and environmental agencies should formulate and enforce policies encouraging the adoption of NF systems in both public and private sectors.

CONCLUSION

The research confirms that nanofiltration is a highly efficient technique for wastewater treatment and reuse. The treated water meets the required environmental standards and can be safely reused for various non-potable purposes, including irrigation, industrial processes, and municipal services. The removal efficiency increases with pressure, but membrane fouling and cost remain critical challenges. Therefore, while NF technology presents an effective solution to address water scarcity and environmental concerns, its practical application requires technical optimization and policy support to ensure economic feasibility and sustainable implementation.

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