ICA2025OSLO
14th IWA Specialised Conference on Instrumentation, Control and Automation

# Membrane Fouling: How Data-Driven Approaches Enhance Monitoring & Control Strategies?

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## Abstract

Membrane fouling remains a critical challenge in membrane filtration, reducing efficiency and increasing operational costs. This review evaluates advancements in Data-Driven monitoring and control systems, highlighting the application of diverse Artificial Intelligence and Machine Learning (AI/ML) methods, alongside Non-Data-Driven approaches. These methods leverage real-time data and predictive analytics to enhance adaptability, operational efficiency, and provide actionable insights for decision-making. However, challenges such as limited scalability, insufficient integration of monitoring and control mechanisms, lack of real-world validation, and limited availability of high-quality datasets hinder broader adoption. Additional barriers, including high computational demands, narrow foulant applicability, and risks of overfitting, emphasise the need for innovative frameworks to bridge the gap between research and practical implementation.

**Keywords:** Data-Driven Monitoring; Data-Driven Control; Water Treatment; Fouling Management

## Introduction

Membrane filtration is a widely adopted water purification technology; but fouling continues to pose significant challenges, affecting efficiency and overall system performance. Fouling involves particles buildup on the membrane, reducing permeability and increasing resistance. This reduces flux, increases pressure, and raises energy use. Accordingly, addressing fouling is essential for maintaining water treatment efficiency and extending membrane lifespan (Chang et al., 2019). Traditional fouling management methods are reactive, addressing fouling only after significant performance losses (Abuwatfa et al., 2023). Recent advancements in data-driven approaches, incorporating the Internet of Things (IoT), real-time analytics, and advanced analytical methods, have enabled proactive solutions to optimise system performance and mitigate fouling (Garg et al., 2024).

This review evaluates state-of-the-art techniques, research efforts, gaps, and challenges in data-driven monitoring and control of membrane fouling for water treatment applications. Based on 112 publications (2015–2024) from Web of Science, SCOPUS, Google Scholar, and Connected Papers, it examines trends in Data-Driven, Non-Data-Driven approaches, along with advancements in real-time systems, dynamic data fusion, and adaptive frameworks. The review highlights key areas such as transitioning from lab to full-scale applications, optimising cleaning strategies, and integrating predictive insights into operations while identifying critical gaps to guide future innovations in membrane filtration.

**Data-Driven Monitoring of Membrane Fouling:** Data-driven monitoring systems use real-time data and advanced algorithms for proactive membrane fouling management (Abuwatfa et al., 2023). Based on the reviewed studies, Non-Data-Driven methods, such as Electrochemical Impedance Spectroscopy, Scanning Electron Microscopy, and Raman Spectroscopy, provide detailed insights into fouling behaviour but are limited by scalability and operational costs. In contrast, Data-Driven approaches, including Artificial Neural Networks, Random Forest, and Support Vector Machines, demonstrate exceptional predictive capabilities and effectiveness in managing complex fouling dynamics (Lim et al., 2019; Deng et al., 2023).

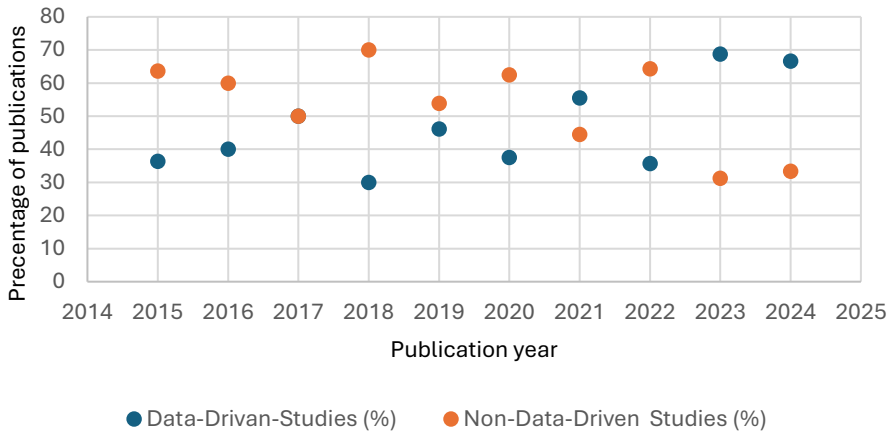


**Figure 1** Annual percentage of Data-Driven and Non-Data-Driven approach publications in monitoring & control of membrane fouling research (2015–2024)

Figure 1 illustrates the increasing popularity of Data-Driven approaches for monitoring and control membrane fouling over the years. While the use of Non-Data-Driven methods has steadily declined, Data-Driven related research has grown significantly, particularly after 2020. This trend highlights a clear shift toward adopting intelligent algorithms for fouling monitoring and control.

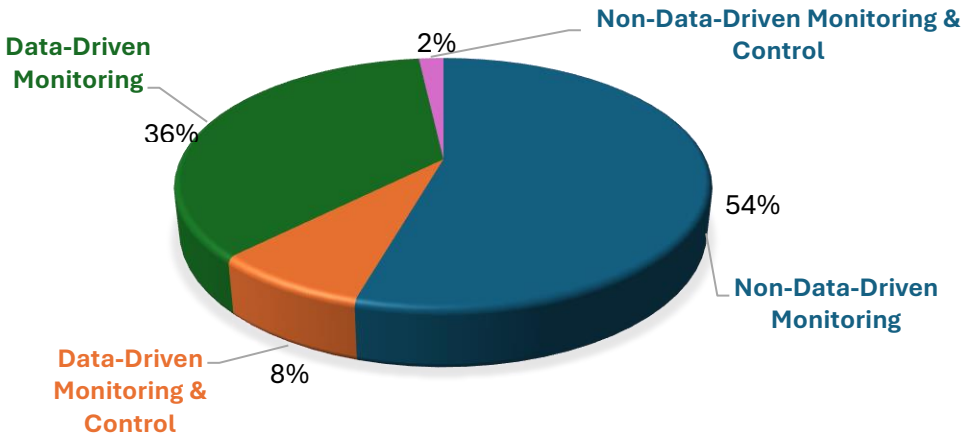


**Figure 2** Distribution of research publications using Data-Driven and Non-Data-driven techniques for membrane fouling studies (2015–2024).

Integrated systems enable real-time adjustments to operational conditions, predictive interventions to prevent fouling, and optimised resource utilisation, making them crucial for effective and sustainable fouling management (Lim et al., 2019). Figure 2 illustrates the distribution of research efforts, highlighting the limited focus on integrated monitoring and control strategies needed for proactive fouling management and resource optimisation.

**Data-Driven Control of Membrane Fouling:** The integration of monitoring and control systems is critical for managing membrane fouling effectively. Real-time systems enhance efficiency by analysing data continuously, enabling dynamic adjustments to operational strategies and improving resource utilisation. Non-Data-Driven methods provide robust frameworks for identifying fouling trends and supporting proactive interventions. Hybrid approaches combining AI/ML model with mechanistic models enhance predictive accuracy and adaptability, directly improving the integration of monitoring with control strategies in dynamic conditions. (Ridwan et al., 2023; Garg et al., 2024).

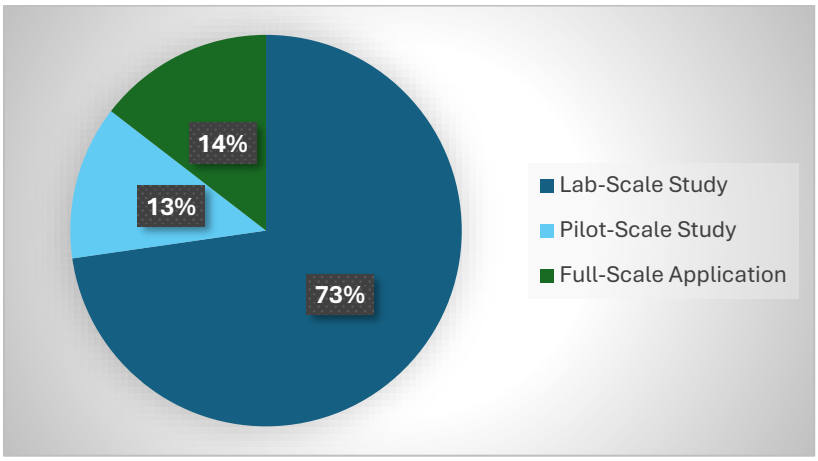


**Figure 3** Distribution of studies by implementation level: Lab-Scale, Pilot-Scale, and Full-Scale applications in membrane fouling research (2015–2024)

According to Figure 3, laboratory-scale studies dominate the field, comprising 73% of reviewed research, while only 13% and 14% have advanced to pilot- and full-scale applications, respectively. This disproportion underscores a critical gap between experimental development and real-world deployment. To bridge this gap, it is essential to strengthen pilot-scale testing and establish robust, scalable methodologies that support the effective translation of data-driven monitoring and control strategies into operational membrane systems.

## Challenges and research gap

Key challenges and research gaps identified across the past decade of studies include limited scalability (over 40%) and insufficient integration of monitoring and control mechanisms (over 25%). Additionally, a lack of real-world validation (over 15%) and limited availability of high-quality datasets (over 5%) were frequently reported. Other challenges, such as high computational demands, narrow foulant applicability, and risks of overfitting, further hinder the broader adoption of advanced monitoring and control strategies.

## Conclusion

Data-driven approaches are transforming membrane fouling management by integrating advanced monitoring with real-time control. The synergy between AI/ML models and mechanistic frameworks enhances predictive accuracy and operational efficiency, particularly under dynamic conditions. However, key challenges persist, such as limited data quality, scalability issues, and weak integration between monitoring and control systems. Bridging the gap between lab-scale development and real-world implementation is essential. To fully realise the benefits of these technologies, future efforts must focus on developing robust, adaptive monitoring–control solutions that function reliably in real-time and scale effectively across diverse water treatment environments.

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