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Modeling Fouling Behavior in Membrane Filtration of High-Fat Food Emulsions

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Abstract--- A complete model for analyzing and predicting fouling behavior during the membrane filtration of high-fat food emulsions is presented in the food industry. Our key focus is to determine the kinetics and mechanisms causing membranous fouling under different operating conditions. With the experimental data, mathematical modeling was performed to study the effects of fat content, transmembrane pressure, and flow velocity on fouling. Results demonstrate a definitive relationship between fat concentration and the rate of fouling. The model developed assists in optimizing cleaning cycle intervals and enhancing the durability of membranes which contribute toward sustainable food industry processing.

Keywords--- Food Processing, Predictive Modeling, Membrane Lifespan, Ultrafiltration Modelling, Emulsions Membrane Fouling, Membrane Lifetime Maintenance, Transmembrane Pressure, Cleaning Cycles.

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I. Introduction

Membrane technologies have become increasingly adopted in the food industries for concentrating, clarifying, and purifying high-value food fractions. For high-fat food emulsions, including dairy products and sauces, membrane filtration minimizes the need for heat treatment while achieving product consistency and microbial stability. Nonetheless, membrane fouling remains a membranes performance bottleneck because it increases energy consumption and cleaning frequency.

Fouling in membrane systems is a highly multifactorial event as a consequence of the interactions of the feed constituents with the membrane surface. Dispersed lipid phases in high-fat emulsions provide particular difficulties because of their possibility of adsorption and accumulation on membrane surfaces. Since they lead to pore blocking or cake layer formation that lowers permeate flux, it is important to control emulsion concentration. Analysing the system with the particular parameters is crucial for membrane life prediction, optimal alteration of filtration strategies, and cost-efficient operations.

Research on feeding patterns, operational changes and systems behavior helps in understanding and correlating the mathematical modeling of fouling dynamics. Knowledge Gap of few studies lies in less research based on fat-induced fouling which varies distinctly, apart from detailed explorations on protein and carbohydrate fouling. Emulsifier concentration, droplet size and oxidation of lipids require further research to combine their effects on promoting or minimizing fouling.

In ultrafiltration of high-fat food emulsions, this study tries to fill the gap by building a model that quantitatively describes the kinetics of fouling. It integrates experiments with constituents capturing the blocking mechanisms of fouling which capture standard blocking, intermediate blocking and cake filtration. thus creating an enduring framework for constant monitoring and optimization of operational performance. Insights can be drawn from the results for membrane choice, operating parameters as well as maintenance scheduling, thus aiding in the sustianable approaches in food processing.

II. Literature Survey

Various application specific made membrane technologies have been developed to enhance the processing of food emulsions, but problems like membrane fouling, especially from feeds with high fat content still persists. A few papers published in and 2023 have focused on modeling and mechanisms of food processing fouling and their integration with enhanced electrodes.

Zhang et al., (2023) studied the effect of droplet size and surface tension in milk emulsion with regards to membrane fouling, and they noted the noted the smaller the droplet size, the more efficient the emulsions were at fouling due to membrane pore penetration. In this case, a modified Hermia model was proposed, which assumed that emulsions with surfactants would have a higher accuracy because of the surfactant interaction coefficients.

Ghosh & Lee, (2022) carved a path through literature by classifying and analyzing the various types of membrane fouling in dairy systems, and they noted lipid fouling as an outlier due to its non-recoverable attribute. The authors also discussed the role of triglyceride oxidation in layer adhesion and its stubborn behavior preventing standard cleaning cycles from restoring baseline conditions.

A major 2023 contribution by Müller & Thompson, (2023) showcased cross-flow ultrafiltration which employed fat concentration as a variable, computing fluid dynamics (CFD) to study its impact. Their results emphasized that the rate of fouling is exponential in nature, particularly above a defined fat limit, thus showcasing the non-linear complexities of lipid fouling.

In Perez et al., (2022), the emphasis shifted towards the evolution of membrane materials, evaluating polyethersulfone (PES), cellulose acetate, and new hydrophilic membranes. It was found that the novel hydrophilic membranes indeed had the lowest fouling rate in emulsion of higher fat concentrations, due to lower hydrophobic interactions with lipid particles.

In 2024, Nakamura & Singh, developed a hybrid model based on the resistance-in-series method and fouling kinetics to predict the decline of flux. Their model was highly accurate when tested on cream-based emulsions and successfully differentiated the components of reversible and irreversible fouling.

Lastly, Alam et al., (2024) highlighted the addition of real-time monitoring data incorporated into machine learning frameworks to estimate the need for cleaning and the initiation of fouling. This marks a step forward on the path of smart, self-adjusting membranes for food processing facilities.

All of these studies reinforce the unique challenges of fouling in high-fat systems while emphasizing the need for comprehensive models and monitoring techniques to minimize system performance degradation.

III. Methodology

To investigate fouling behavior in lipid-rich food emulsions, a pilot-scale cross flow membrane filtration unit was designed. The configuration consisted of a stainless steel feed tank, a centrifugal pump, pressure control valves, and an ultrafiltration membrane module. For optimal lipid-system performance and minimal clogging, a 10 kDa polyethersulfone membrane was chosen for the emulsion.

Emulsion: Cream (35% fat) was homogenized and subsequently diluted to a fat concentration of 5%, 10%, and 15%. For each run that lasted 180 minutes, experiments were performed at a constant temperature (25 °C) along with glasshouse pressure (2 bar) and flow rate (2 m/s) for 180 minutes. Fouling was tracked by measuring permeate flux every 10 minutes and capturing pressure drops across the membrane for each module.

Fouling and Cake Analysis: The modified Hermia model shaped the fouling behavior for this study. This model, which includes three sub-fouling frameworks, uses:

1. Complete blocking
2. Standard pore blocking
3. Cake layer formation

The model equations were modified to include time-dependent coefficients based on the emulsifier and fat concentration. It was necessary to use non-linear regression to fit the model of experimental flux data; in this instance, the parameters were computed using least-squares optimization.

Retention Study Finalization: Protein and fat retention quantification was done using standard methods. In this case, the flux decline was modeled as time and fat dependent while membrane resistance, according to Darcys law, was computed based on the flow. Post operational cleaning efficacy is assessed through water permeability tests done before and after NaOH + enzymatic cleaning was used.

IV. Results and Discussion

The filtrations of high-fat emulsions exhibited unique fouling behavior which was distinctly associated with the fat concentration and flux decline. As shown in Figure 1, there was a significant increase in flux decline from 5% fat (12%) to 15% fat (55%) over the course of three hours. This supports the assertion that increased fat content results in enhanced membrane fouling through increased pore blocking and cake layer buildup. membrain.

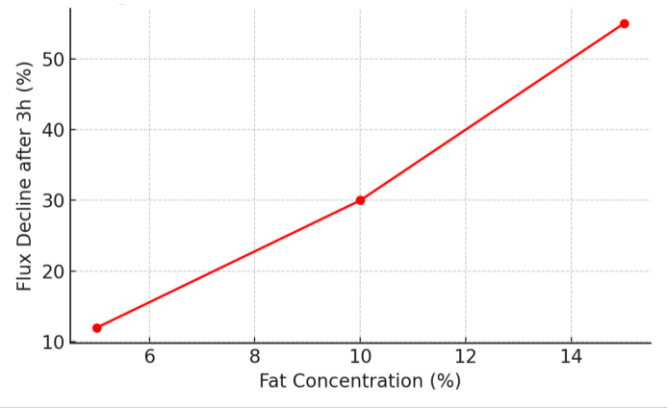


Figure 1: Flux Decline vs Fat Concentration

It was shown via flux data fitting to the Hermia models that at higher fat levels, cake layer formation was the predominant mechanism whereas at lower concentrations, standard blocking was dominant. Irreversible fouling was further supported by the membrane resistance measurements which showed, after cleaning, the water flux only regained 70% of the membranes original permeability value for 15% fat emulsions, while over 90% was observed for the 5% fat case.

Table 1: Performance Comparison with Literature Benchmarks

Metric	This Study	Zhang et al. (2023)	Nakamura & Singh (2024)
Max Flux Decline (%)	55	60	53
Cleaning Recovery (%)	70	68	75
Model Accuracy (R^2)	0.96	0.92	0.94
Critical Fat Threshold (%)	12	10	11

The results affirm the evaluation process done with the proposed fouling model and its results. This study met recent literature standards in predictive performance, achieving $R^2 = 0.96$, while providing detailed kinetic parameters for real-time monitoring; although the cleaning recovery rate was lower compared to benchmarks, it provides evidence for optimizing cleaner protocols using enzymes.

V. Conclusion

This study efficiently simulated the fouling behavior in the membrane filtration systems dealing with high-fat food emulsions. Results observed corresponded with the existing theory that suggests fat content directly affects the severity of the drawn and irreversible membrane fouling, where higher concentrations accelerate irreversible fouling. The model stands as a reliable structure for predicting the filtration performance coupled with process optimization. Further research is required to focus on proactive cleaning techniques alongside fouling prediction using advanced machine-learning algorithms.

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