ANALYZING FLOW DYNAMICS WITH 3D PRINTED TURBULENCE PROMOTERS IN ULTRAFILTRATION UNIT TO MITIGATE MEMBRANE FOULING

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Abstract
This study investigates the impact of various *3D* printed turbulence promoters (*3DPTP*) in a lab-scale low-pressure ultrafiltration membrane separation stirring unit using dairy model wastewater effluent. The research focuses on evaluating the performance of different *3DPTP* shapes; and identifying the optimal *3DPTP* material for the unit based on the best-performing shape. Multiple *3DPTP* designs were developed, fabricated, and tested using various materials to assess key membrane separation parameters, such as permeate flux, membrane retention, and total, reversible, and irreversible resistances. Specific *3DPTP* designs, particularly *PLA-UE* and *PLA-S*, significantly enhanced average permeates flux and reduced the total resistance. Among the tested materials, the resin material demonstrated superior performance by notably increasing permeate flux and reducing total resistance. Statistical analysis was employed to confirming the influence of *3DPTP* designs and materials on the separation performance.

Introduction
The escalating environmental challenges, driven by rapid population growth, have highlighted the importance of protecting natural water resources [1]. Within the food industry, particularly in dairy operations, substantial water use and wastewater management present significant issues [2]. The need for advanced technologies, such as hybrid/combined processes, for managing high-organic-content wastewater has become critical. Ultrafiltration, a membrane-based process, is increasingly utilized in industrial and wastewater treatment applications due to its effectiveness. However, membrane fouling and concentration polarization are persistent challenges in these processes [3]. Mitigating membrane fouling requires optimizing membrane parameters, including transmembrane pressure, stirring speed, and membrane cut-off values, as well as enhancing hydrophilicity to reduce fouling [4]. Additive manufacturing (*3D* printing) has emerged as a solution, enabling the fabrication of complex geometries and addressing various industrial challenges. The use of *3D* printed turbulence promoters (*3DPTP*) into the membrane filtration units has shown significant potential in reducing membrane fouling. Studies have demonstrated the effectiveness of *3DPTP* in improving energy efficiency and reducing fouling in membrane distillation processes. Optimizing the geometry of *3DPTP* has enhanced mixing and membrane performance. Moreover, the integration of *3DPTP* as led to superior fouling resistance and increased output flux compared to traditional spacers [5].

This study aims to examine the operational parameters of ultrafiltration membranes in a laboratory-scale dairy wastewater treatment model. After determining optimal parameters, the impact of *3DPTP* shapes on filtration efficiency and the effect of various materials on filtration performance were evaluated through comprehensive statistical analyses. The study uniquely addresses the shape and material analysis of *3DPTP* in small-scale membrane separation units.

Experimental

Model Wastewater Preparation

Model effluent simulating dairy wastewater was prepared using skimmed milk powder and anionic detergent dissolved in tap water at 25°C, achieving concentrations of 5 g/L and 0.5 g/L, respectively. Parameters such as chemical oxygen demand (*COD*) (5200 mg/L), turbidity (1150 NTU), conductivity (0.89 mS), and pH (8.7) were recorded.

Membrane Filtration Equipment

A static, stirred ultrafiltration system (Merck Millipore, Germany) was used in the laboratory. The apparatus utilized *PES* (polyethersulfone) membranes with various cut-off values, providing a total effective filtration area of 0.0036 m^2. Transmembrane pressure was controlled by nitrogen gas from a cylinder, regulated via a pressure valve. Filtrate was discharged through a tube at the base, maintaining a volume reduction ratio (*VRR*) of 2, reducing volumes from 100 mL to 50 mL. The mass of the permeate was continuously monitored using an electric balance (Kern EW, Germany).

Measurements for Shape and Material of 3DPTP

After selecting the optimal parameters, all variable settings associated with the equipment were documented. Measurements were then conducted using four different designs for shape testing (polylactic acid -unrestricted endstarting (*PLA-UE*), Polylactic acid-slim (*PLA-S*), polylactic acid thin barrier (*PLA-TB*) polyamide dual barrier (*PA-DB*)), and simultaneously, four identical designs were used for material testing (*PLA*, Resin, Metal, and thermoplastic polyurethane (*TPU*)), with *3DPTP* of various materials inserted along with control measurements, which were then repeated. The ultrafiltration measurements were carried out similarly to the initial series of experiments, except that the selected *3DPTP* was also directly placed on the membrane surface inside the device.

Results and discussion

The evaluations of various *3DPTP* designs showed differences in average flux. Figure 1 shows that the *PLA-UE* and *PLA-S* designs provide significant improvements in flux values compared to the control and the other designs. Additional testing with alternative printing materials demonstrated notable gains in average flux, particularly with resin material, which also contributed to decreased total resistance. Overall, the findings underscore the critical role of *3DPTP* in enhancing ultrafiltration performance.

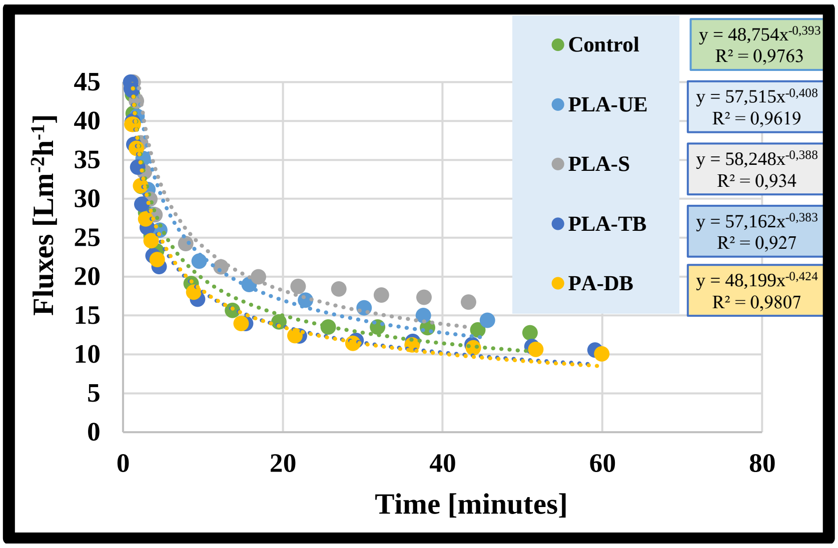

Figure 1. Variation of permeate fluxes as a function of time with different *3DPTP* (20 kDa *UF* membrane, T = 25°C, *TMP* = 3 bar, n = 400 rpm).

Conclusion

This study investigates the effects of 3D printed turbulence promoters (*3DPTP*) in a laboratory-scale ultrafiltration membrane separation unit using dairy model effluent. Various designs of *3DPTP* were tested, along with different materials, to evaluate key ultrafiltration parameters: permeate flux, membrane retention, and total resistance. The experiment with different 3D printed promoter designs revealed variations in average flux, with the *PLA-UE* and *PLA-S* designs showing notable improvements. Further assessments with alternative printing materials highlighted substantial gains in average flux, especially with resin material, which also decreased total resistance. The findings demonstrate the significant impact of *3DPTP* on ultrafiltration efficiency, with the *PLA-UE* design and resin material showing the most promising results in improving flow dynamics and overall performance.

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