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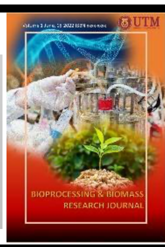

Research Article

Influence of Hydrodynamic Factors on the Biofilm Deformation in Membrane Aerated Biofilm Reactor (MABR) using Fluid Structure Interaction (FSI)

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ARTICLE INFO

Article History:
Received 18 November 2025
Received in revised form 28 December 2025
Accepted 29 December 2025
Available online 30 December 2025

Keywords:
Membrane aerated biofilm reactor,
Immobilised biofilm,
Fluid structure interaction,
COMSOL,
Wastewater treatment

ABSTRACT

Membrane aerated biofilm reactors (MABR) have emerged as a promising alternative for wastewater treatment, yet their performance is often limited by an incomplete understanding of the fluid structure interactions (FSI) that influence biofilm behaviour and mass transfer. This knowledge gap hampers the optimisation of MABR design for efficient pollutant and nitrogen removal. The main purpose of this study is to investigate the impact of the hydrodynamic factors on the biofilm deformation to achieve better performance of the MABR during the wastewater treatment process. The experimental setup has a limitation towards the investigation of the hydrodynamics factors, by applying the FSI of COMSOL® Multiphysics 5.3 software for data analysis, focusing on the hydrodynamic factors. It was found that at a lower inlet velocity (8.33 μm/s), the formation of biofilm thickness was greater (32 $\mu\mathrm{m}$) in the rough surface as compared to the flat surface, which was 22 μm. This study also found that the shear stress generated was proportional to the inlet velocity and had an opposite effect on biofilm formations. The COMSOL simulations indicated that a decrease in Young's modulus (70 Pa) had increased the rate of biofilm deformation to 6 $\mu\mathrm{m}$ for the rough surface and 2 $\mu\mathrm{m}$ for the flat surface. This work has successfully justified the hydrodynamic factors pose a significant impact on the formation and deformation of the biofilm.

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DOI address: 10.11113/bioprocessing.v4n2.84

INTRODUCTION

Bacteria are single-celled organisms that belong to the prokaryotes. Recent characterisation research has shed light on the intricate nature of microbial biofilm formation (Dsouza et al., 2024). Microorganisms can appear or live in two forms: the free-floating form, as in the planktonic state, or in a consortium. The microorganisms can live in a consortium either within the same species or different species. This phenomenon is known as biofilm (Rather et al., 2021). Biofilm has been present on earth for around 3.4 billion years (Guzmán-Soto et al., 2021). The movement of bacteria to form a community attached to a surface is because of the physical forces such as Brownian diffusion, gravitational settling, and hydrodynamic forces (Ammar et al., 2015). Bacterial biofilms are enclosed or embedded in a self-secreted matrix of extracellular polymeric substances (EPS) (Maric, S., and Vranes, J., 2007). Biofilm formation is a complex process that involves a multi-step process to transform the free-floating bacteria in the planktonic form into a biofilm-making sessile form. The whole biofilm formation process can be divided into five main stages, such as initial reversible attachment, irreversible attachment, biofilm architecture development, maturation, and escape (Rather et al., 2021, Alotaibi, 2021 & Brading, 1995). The complex structure of the bacterial community has impacted various sectors and raised concerns in public health, medicine and industries (Dsouza et al., 2024). In contrast to causing shortfalls, there are also potential applications of the biofilm. For instance, bioremediation, fermentation, wastewater treatment and agriculture (Werkneh, 2022, Coenye & Nelis, 2010).

As reported, the problem with the MABR is uncontrolled biofilm thickness formations, as it plays a crucial role in the MABR effectiveness during wastewater treatment (Li, X., et. al., 2023, Siddiqui et al., 2022 & He et al., 2021). The biofilm formation had stimulus the substrate diffusion rate from the bulk liquid to the biofilm, simultaneous nitrification and denitrification rates, chemical oxygen demand (COD) removal rates and microbial interactions within the biofilm (Li et. al., 2023 & Sanchez-Huerta et al., 2022), resulting in concerns for increased mass transfer resistance and membrane clogging issue (He et al., 2021).

Hydrodynamic factors play a crucial role in affecting the biofilm formation and deformation. Hydrodynamic factors can be included, such as the shear stress generated and the velocity of fluid flow in a reactor (Chang, et, al., 2020 & Plascencia-Jatomea et. al., 2015) Additionally, the reactor membrane's surface roughness is considered one of the hydrodynamic factors that can affect the biofilm thickness on the reactor membrane. Therefore, understanding the influence of hydrodynamic factors can help optimise biofilm growth in the reactor, thereby improving overall wastewater system performance. To achieve this, fluid structuree interaction (FSI) is well known as a mathematical simulation which can provide relevant data for biofilm formation. FSI performs the interaction between the fluid flow and the structural mechanics, which in the project is the interaction of the wastewater flow with the biofilm structure. Therefore, it can provide a better understanding of the effect of hydrodynamic factors on the biofilm deformation. Besides, FSI can provide flexibility for simulating changes in design and operational parameters to predict system response (Casey, 2007).

MATERIALS AND METHODOLOGY

Simulation Materials and Software

In this study, SOLIDWORK® software (Version 2022) was implemented to develop the membrane aerated biofilm reactor (MABR). The selected boundary conditions were accurate and reliable for performing the computational fluid flow behaviour. Fluid structure interaction (FSI) was performed using COMSOL® Multiphysics 5.3 software to investigate and simulate the hydrodynamic flow conditions in the MABR.

Modelling Approach and Simulation Setup

The overall workflow of this project began with data validation, followed by two-dimensional (2D) and three-dimensional (3D) modelling and model construction using COMSOL® Multiphysics 5.3 software. For data validation of the model, the fluid and solid mechanics materials selection was wastewater and biofilm deformation, respectively. **Table 1** showed the parameters set in the COMSOL® Multiphysics 5.3 software for the simulation study. The inlet and outlet conditions, such as pressure and inlet velocity, were defined. For the inlet stream, the inlet velocity was defined, whereas for the outlet stream, the pressure is described. The pressure of the outlet stream was assumed to be zero due to the laminar flow. For the development of the mesh element, a mesh convergent test was conducted for the selection of meshing type. A test needed to be undertaken by the trial-and-error method. Each mesh size was applied to the model and allowed for the simulation until a constant result was obtained (Musfirah, 2019).

Table 1 Parameters set in COMSOL for the simulation study.

No	Parameters	Values	Applied to
1	Inlet Velocity $\left[\frac{\mu m}{s}\right]$	8.3335, 180.6635, 352.9935, 525.3335	Inlet surface
2	Pressure	0	Outlet surface
3	Young's Modulus	700 - 70	Solid mechanic
4	Poission Ratio	0.4	Solid mechanic

Once validated, the MABR structural model was developed in SOLIDWORK® software (Version 2022), as shown in **Figure 1**. However, the material selection for both fluid and solid mechanics for the MABR is wastewater and biofilm, respectively. A mesh convergence test was then conducted in COMSOL to optimise the mesh size, ensuring a balance between simulation accuracy and computational efficiency (Musfirah, 2019). The test was repeated until the mesh size was validated, then the simulation was run in COMSOL® Multiphysics 5.3.

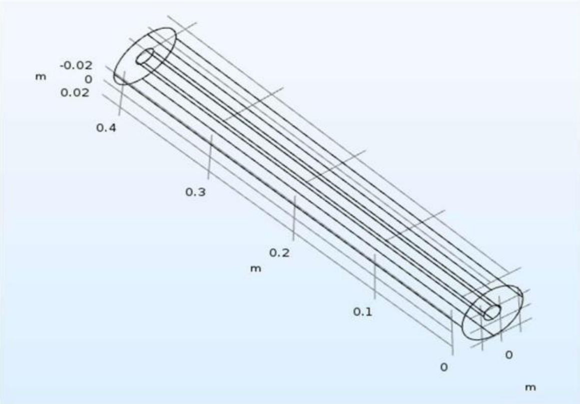

Figure 1 3D MABR model constructed using SOLIDWORK® software (Version 2022).

RESULTS AND DISCUSSION

The simplified MABR model was developed in SOLIDWORK® software (Version 2022), while the interaction between fluid mechanics and solid mechanics, referred to as the biofilm, was analysed using COMSOL® Multiphysics 5.3 software. In this study, the impact of various hydrodynamic factors on biofilm deformation in the MABR was analysed.

Model Validation

In this project, the simulation in COMSOL Multiphysics 5.3 was validated against the journal articles by Wei & Yang (2023) and Picioreanu et al. (2018). The validation was done by constructing a similar experimental setup in COMSOL® Multiphysics 5.3 software using the references from the journal (Wei & Yang, 2023; Picioreanu et al., 2018). Data validations were performed on 2D and 3D models to obtain more accurate results. For good data validation results, the percentage differences between the established data and the COMSOL® Multiphysics 5.3 software simulation should not exceed 15 % using the equation below:

$$Percentage\ error\ =\ \left(\frac{COMSOL - Journal}{Journal}\right) \times 100\%$$

Effect of Surface Roughness on Biofilm Deformation

Figure 2 illustrates the relationship between biofilm thickness and shear stress for circular and flat surfaces, as determined from COMSOL® Multiphysics 5.3 software simulations that align with previously studied results, as shown in **Figure 3** (Wei & Yang, 2023). **Figure 2** and **Figure 3** show similar trends whereby biofilm thickness decreased as the shear stress increased. Both figures also indicated that the circular surface has higher biofilm thickness formations as compared to the flat surface.

At the same shear stress, the average biofilm thickness developed was consistently higher for the circular surface as compared to the flat surface. The effect of surface roughness on bacterial adhesion and biofilm formation has been extensively investigated. The increase in the development of the biofilm at the circular surface was likely caused by the increase in the surface area availability for bacterial attachment by providing a scaffold for adhesion (Yoda., et. al., 2014). Besides, the surface roughness provides a low velocity and shear stress region for the bacteria to grow (Bollen., et. al., 1996), thereby resisting the detachment of the attached bacteria. The presence of surface roughness provided sheltered regions, which increased the area with lower velocity and shear stress.

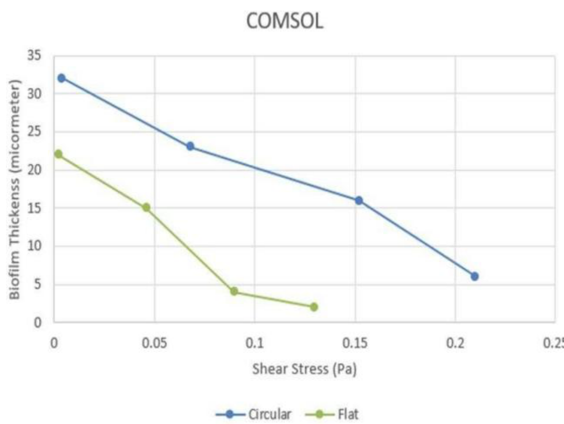

Figure 2 The comparison between biofilm thickness and shear stress for circular and flat surfaces obtained from the COMSOL® Multiphysics 5.3 software simulation.

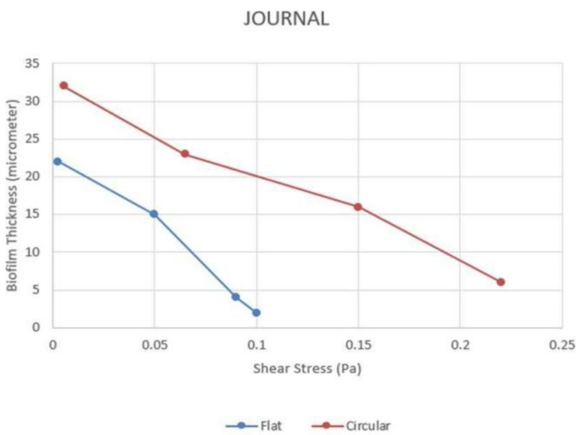

Figure 3 The comparison between biofilm thickness and shear stress for circular and flat surfaces (Wei, G., et al. 2023).

Comparison Between 2D and 3D Simulation Models

Figure 4 presents the 3D flat surface model generated using COMSOL® Multiphysics, which visualises the velocity field distribution within the MABR. The highest velocity is observed at the flow centre, whereas velocities near the wall approach zero due to the no-slip boundary condition. This parabolic velocity profile confirms that the system operates under laminar flow (Sharma et. al., 2011), a condition crucial for analysing shear stress and its impact on biofilm stability.

Figure 5 compares the results obtained from the 2D and 3D simulations on a flat surface. To validate the computational approach, identical simulation settings were used in the 3D model. At the same time, the inlet velocity was increased from 8.33 µm/s to 525.33 µm/s, resulting in an increase in the generated shear stress from 0.0021 Pa to 0.1300 Pa. **Figure 5** also shows a similar pattern of shear stress between the 2D and 3D simulations, demonstrating strong agreement between the two models. This correlation confirms the reliability of the simulation setup and indicates that the 2D model can adequately represent hydrodynamic behaviour with minimal inaccuracy when dealing with the deformations of biofilm.

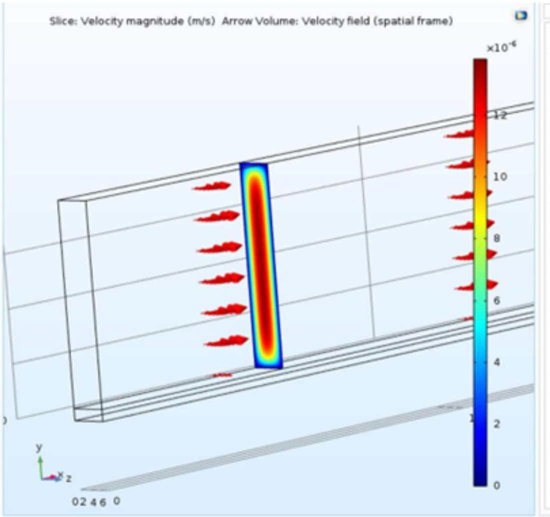

Figure 4 3D flat surface model

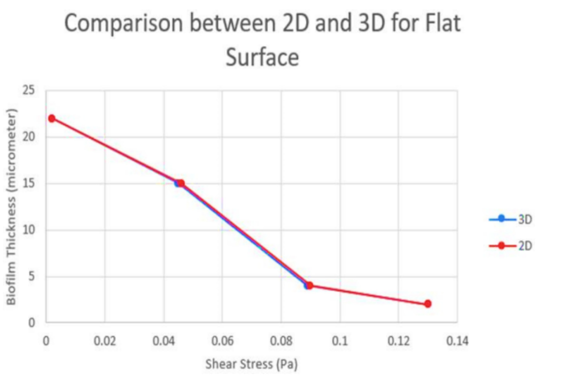

Figure 5 Comparison of the shear stress and biofilm thickness obtained from 2D and 3D simulations on a flat surface

MABR Velocity and Flow Characteristics

The 3D MABR model was constructed using SOLIDWORK® software (Version 2022) as shown in **Figure 1**. A mesh convergent test was conducted, shown in **Table 2** for the 2D MABR model, starting from extremely coarse to extremely fine. As the results, the meshing started to converge at the mesh type of extra fine as reported previously (Musfirah, 2019). The shear stress obtained increased significantly from extremely coarse to fine. Then, the shear stress increased less significantly from 0.065 at finer meshing to 0.068 at extra fine and eventually reached a constant shear stress value at 0.068 at extremely fine. This mesh convergent test indicates that the simulation results began to converge at the extra fine meshing. The further increase in the meshing did not affect the simulation results.

Figure 6 below shows the velocity profile in the MABR. The outer tube of the reactor was filled with a wastewater stream that fed from the bottom, whereas the inner tube was filled with an oxygen supply from the top. The biofilm was growing on the surface of the inner tube due to the different velocity profile and shear stress. The inner tube was porous, semi-permeable to the diffusion of oxygen to the biofilm layer. The presence or supply of oxygen to biofilm encourages the development of the biofilm (Casey, et. al. 2020). The wastewater stream that is being fed into the outer tube space comes into contact with the biofilm to be treated and is released as clean water from the top of the MABR.

Table 2 Mesh convergent test

Type of Meshing	Shear Stress (Pa)
Extremely Coarse	0.0042
Extra Coarse	0.0044
Coarser	0.0045
Coarse	0.0046
Normal	0.0056
Fine	0.0059
Finer	0.0065
Extra Fine	0.0068
Extremely Fine	0.0068

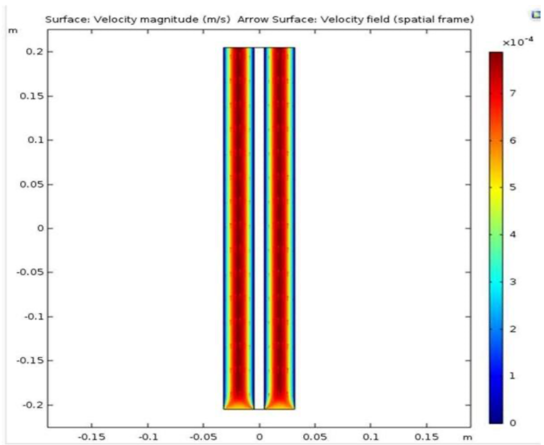

Figure 6 Velocity profile obtained from a simulation study using the MABR model

Influence of Biofilm Stiffness (Young's Modulus)

Stiffness is another critical factor that affects bacterial adhesion and biofilm formation. Young's modulus, which is defined by the ratio of stress to strain, is a common parameter used to represent stiffness. A low Young's modulus indicates that the material is softer and more elastic. Picioreanu et.al. (2018) have conducted an assessment of the elastic Young's Modulus value. The assessment was conducted to investigate the deformation of biofilm with different Young's Modulus values applied, as shown in **Figure 7**. The evaluation was done by performing a parametric sweep over a range of Young's modulus values to find the best fit for the computed deformation to the measured deformed biofilm geometry. Young's modulus is a measure of material stiffness. As a result, large deformations occur at a smaller value of the Young's modulus. The study also showed that the compression occurs at the biofilm frontal zone, and traction takes place on the upper biofilm sections. A smaller Young's modulus value can lead to a rapid degradation and deformation of the structure. This is because a smaller Young's modulus indicates softer and more deformable biofilm materials. COMSOL simulations had shown a similar trend. As the Young's modulus values decreased from 700 Pa to 350 Pa followed by 70 Pa, the deformation of the biofilm increased within the range 32 - 2 µm.

Effect of Inlet Velocity on Shear Stress and Deformation

The microstructure of biofilm that developed under a slower velocity environment was found to be thicker and had larger surface sinuosity and higher areal densities as compared to the biofilm that was exposed to higher velocity flow (Lecuyer, et. al., 2011). Surface sinuosity and biofilm fragmentation increase with the biofilm thickness. Hence, a larger surface sinuosity of a biofilm refers to the increased complexity or irregularity in the surface structure of the biofilm. At the high velocity flow rate, the Reynolds number (R_e) shows turbulent flow in the streamside flumes. Turbulent conditions eventually lead to an increase in shear stress. As a result, the fast velocity flow shows a higher shear stress value as compared to the slow velocity flow. With the presence of high shear stress, the biofilm's deformation rate increases. As mentioned, the increase in biofilm thickness increases surface sinuosity, biofilm fragmentation, and areal density. Hence, all these parameters show a higher value in the slow flow velocity than in the fast flow velocity.

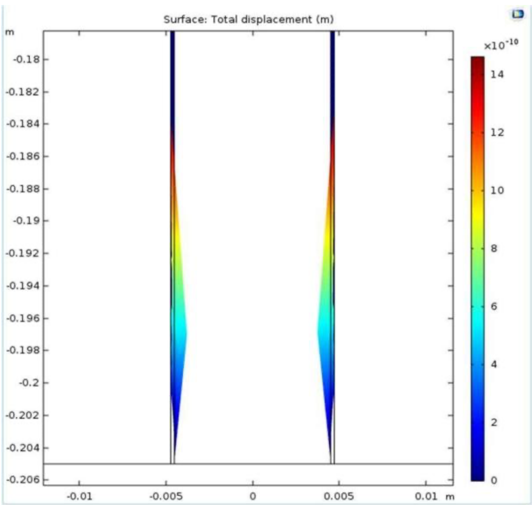

Figure 7 Deformation of biofilm

CONCLUSION

The outcomes of the simulation using COMSOL® Multiphysics 5.3 were successfully validated. The run simulation clearly shows that the hydrodynamic factors have a significant impact on the deformation of biofilm. The biofilm thickness is greater on a rough surface than on a flat surface, as it provides a surface area with lower shear stress for the bacteria. In addition, through simulation, it has justified that the shear stress generated is proportional to the inlet velocity. As the inlet velocity increases, the shear stress generated by acting on the biofilm layer also increases. The higher the amount of shear stress generated, the greater the rate of biofilm deformation. The relationship between the Young's modulus value and the rate of biofilm deformation is also justified. COMSOL® Multiphysics 5.3 software simulations indicate that a decrease in Young's modulus values from 700 Pa to 350 Pa followed by 70 Pa increases the rate of biofilm's deformation. The work has successfully justified that the hydrodynamic factors, such as inlet velocity, surface roughness, shear stress and Young's modulus values, pose a significant impact on the deformation of the biofilm layer.

Acknowledgement

The authors would like to express their sincere appreciation to Universiti Teknologi Malaysia (UTM) for providing research facilities and technical support. Special thanks are extended to those involved directly and indirectly for their valuable guidance and assistance throughout the completion of this work.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

References

Alotaibi, G. F. (2021). Factors Influencing Bacterial Biofilm Formation and Development. *American Journal of Biomedical Science & Research*, *12*(6), 617–626. https://doi.org/10.34297/ajbsr.2021.12.001820

Ammar, Y., Swailes, D., Bridgens, B., & Chen, J. (2015). Influence of surface roughness on the initial formation of biofilm. *Surface and Coatings Technology*, *284*, 410-416.

Bollen, C.W., Papaioanno, W., Van Eldere, J., Schepers, E., Quirynen, M., van Steenberghe, D. (1996). The influence of abutment surface roughness on *plaque accumulation and peri-implant mucositis. Clinical Oral Implant Research*, 7(3), 201-211.

Brading, M. G., Boyle, J., & Lappin-Scott, H. M. (1995). Biofilrn formation in laminar flow using Pseudomonas fluorescens EX101. In *Journal of Industrial Microbiology, (*15). https://academic.oup.com/jimb/article/15/4/297/5 9 88571

Casey, E. (2007). Simulation studies of process scale membrane aerated biofilm reactor configurations. 4th International Water Association Membranes Conference, Harrogate, UK. http://hdl.handle.net/10197/4455

Casey, E., Glennon, B., & Hamer, G. (2000). Biofilm development in a membrane-aerated biofilm reactor: effect of intra-membrane oxygen pressure on performance. *Bioprocess Engineering*, *23*(5), 457-465. https://doi.org/10.1007/s004499900175

Chang, J., He, X., Bai, X., & Yuan, C. (2020). The impact of hydrodynamic shear force on adhesion morphology and biofilm conformation of Bacillus sp. *Ocean Engineering*, *197*, 106860. https://doi.org/10.1016/j.oceaneng.2019.106860

Coenye, T., & Nelis, H. J. (2010). In vitro and in vivo model systems to study microbial biofilm formation. *Journal of Microbiological Methods*, *83*(2), 89–105. https://doi.org/10.1016/j.mimet.2010.08.018

Dsouza, F. P., Dinesh, S., & Sharma, S. (2024). Understanding the intricacies of microbial biofilm formation and its endurance in chronic infections: a key to advancing biofilm-targeted therapeutic strategies. In *Archives of Microbiology,* 206(2). https://doi.org/10.1007/s00203-023-03802-7

Guzmán-Soto, I., McTiernan, C., Gonzalez-Gomez, M., Ross, A., Gupta, K., Suuronen, E. J., Mah, T.-F., Griffith, M., & Alarcon, E. I. (2021). Mimicking biofilm formation and development: Recent progress in in vitro and in vivo biofilm models. *IScience*, *24*(5), 102443. https://doi.org/10.1016/j.isci.2021.102443

He, H., Wagner, B. M., Carlson, A. L., Yang, C., & Daigger, G. T. (2021). Recent progress using membrane aerated biofilm reactors for wastewater treatment. *Water Science and Technology*, *84*(9), 2131–2157. https://doi.org/10.2166/wst.2021.443

Lecuyer, S., Rusconi, R., Shen, Y., Forsyth, A., Vlamakis, H., Kolter, R., & Stone, H. A. (2011). Shear Stress Increases the Residence Time of Adhesion of Pseudomonas aeruginosa. *Biophysical Journal*, *100*(2), 341–350. https://doi.org/10.1016/j.bpj.2010.11.078

Li, J., Feng, M., Zheng, S., Zhao, W., Xu, X., & Yu, X. (2023). The membrane aerated biofilm reactor for nitrogen removal of wastewater treatment: Principles, performances, and nitrous oxide emissions. In *Chemical Engineering Journal,* 460:141693. https://doi.org/10.1016/j.cej.2023.141693

Li, X., Bao, D., Zhang, Y., Xu, W., Zhang, C., Yang, H., Ru, Q., Wang, Y. F., Ma, H., Zhu, E., Dong, L., Li, L., Li, X., Qiu, X., Tian, J., & Zheng, X. (2023). Development and Application of Membrane Aerated Biofilm Reactor (MABR)—A Review. In *Water (Switzerland),* 15(3). MDPI. https://doi.org/10.3390/w15030436

Marić, S., & Vraneš, J. (2007). Characteristics and significance of microbial biofilm formation. *Periodicum biologorum*, *109*, 115-121.

Musfirah, A. (2019). Particle Depositions in Multi-Stage Liquid Impinger (MSLI) as Simplified Lung Model using Computational Fluid Dynamiz (CFD), MSc Thesis, UTM Skudai.

Picioreanu, C., Blauert, F., Horn, H., & Wagner, M. (2018). Determination of mechanical properties of biofilms by modelling the deformation measured using optical coherence tomography. *Water Research*, *145*,588–598. https://doi.org/10.1016/j.watres.2018.08.070

Plascencia-Jatomea, R., Almazán-Ruiz, F. J., Gómez, J., Rivero, E. P., Monroy, O., & González, I. (2015). Hydrodynamic study of a novel membrane aerated biofilm reactor (MABR): Tracer experiments and CFD simulation. *Chemical Engineering Science*, *138*, 324–332. https://doi.org/10.1016/j.ces.2015.08.004

Rather, M. A., Gupta, K., & Mandal, M. (2021). Microbial biofilm: formation, architecture, antibiotic resistance, and control strategies. In *Brazilian Journal of Microbiology,* 52(4), 1701–1718. https://doi.org/10.1007/s42770-021-00624-x

Sanchez-Huerta, C., Fortunato, L., Leiknes, T., & Hong, P. Y. (2022). Influence of biofilm thickness on the removal of thirteen different organic micropollutants via a membrane aerated biofilm reactor (MABR). *Journal of Hazardous Materials*, *432*. https://doi.org/10.1016/j.jhazmat.2022.128698

Sharma, C., Malhotra, D., & Rathore, A. S. (2011). Review of Computational fluid dynamics applications in biotechnology processes. *Biotechnology Progress*, *27*(6), 1497–1510. https://doi.org/10.1002/btpr.689

Siddiqui, M. A., Biswal, B. K., Siriweera, B., Chen, G., & Wu, D. (2022). Integrated self-forming dynamic membrane (SFDM) and membrane-aerated biofilm reactor (MABR) system enhanced single-stage autotrophic nitrogen removal. *Bioresource Technology*, *345*, 126554. https://doi.org/10.1016/j.biortech.2021.126554

Wei, G., & Yang, J. Q. (2023). Impacts of hydrodynamic conditions and microscale surface roughness on the critical shear stress to develop and the thickness of early- stage *Pseudomonas putida* biofilms. *Biotechnology and Bioengineering*, *120*(7), 1797–1808. https://doi.org/10.1002/bit.28409

Werkneh, A. A. (2022). Application of membrane-aerated biofilm reactor in removing water and wastewater pollutants: Current advances, knowledge gaps and research needs - A review. In *Environmental Challenges,* 8. https://doi.org/10.1016/j.envc.2022.100529

Yoda, I., Koseki, H., Tomit, M., Shida, T., Horiuchi, H.,Sakoda, H., & Osaki, M. (2014), Effect of surface roughness of biomaterials on Staphylococcus epidermidis adhesion, *BMC Microbiology*, 2;14:234. https://doi.org/10.1186/s12866-014-0234-2