

Synergistic effects of mechanical reciprocation, biogas scouring, and quorum quenching on membrane fouling mitigation in an Anaerobic Migrating Bed Reactor (AnMBR)

Thao Tran Minh

Danang University of Technology and Education, The University of Danang

Hanh Do Hong

Danang University of Technology and Education, The University of Danang

Son Nguyen Hoang Phuc

Danang University of Technology and Education, The University of Danang

Toan Nguyen-Sy

`nstoan@ute.udn.vn`

Danang University of Technology and Education, The University of Danang

Research Article

Keywords: anaerobic membrane bioreactor, membrane fouling, quorum quenching, reciprocation, transmembrane pressure, fouling resistance, Hermia model, PCA

Posted Date: October 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10909874/v1>

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Additional Declarations: No competing interests reported.

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2 **membrane fouling mitigation in an Anaerobic Migrating Bed Reactor (AnMBR)**
3 Tran Minh Thao • Do Hong Hanh • Nguyen Hoang Phuc Son • Nguyen-Sy Toan

4 T. M. Thao • D. H. Hanh • N. H. P. Son • N-S Toan (✉)
5 Danang University of Technology and Education, The University of Danang, 48-Cao Thang,
6 Danang, Viet Nam
7 E-mail: nstoan@ute.udn.vn

ABSTRACT

Membrane fouling remains a major challenge limiting the long-term operation of anaerobic membrane bioreactors (AnMBRs). This study investigated integrated anti-fouling strategies involving abrupt reciprocation, biogas scouring, and quorum-quenching (QQ) microorganisms to improve the hydraulic stability of the membrane in an anaerobic migrating bed reactor coupled with a submerged membrane system. The reactor startup performance was monitored over 17 weeks using chemical oxygen demand (COD) and biochemical oxygen demand (BOD) removal. Membrane fouling behavior was evaluated under different hydraulic fluxes (100, 200, and 400 LMH). The reactor achieved stable startup performance with COD and BOD reductions of 69.0% and 76.7%, respectively. Severe membrane fouling occurred at 400 LMH, where the permeate flow rate decreased by 73.5% within 48 h. Hermia model analysis indicated a transition from pore-blocking to cake-layer-dominated fouling during prolonged filtration. Moderate reciprocation frequencies (30~60 Hz) significantly improved membrane hydraulic performance. Compared with the control system, the QQ-assisted reactor maintained a higher permeate flow rate (53.2 mL/min) and a lower TMP accumulation (60.9 kPa) after 10 days of operation. Quorum quenching also reduced irreversible fouling contribution from 21.7% to 11.1%, indicating improved fouling reversibility. PCA and correlation analyses further confirmed that integrated anti-fouling strategies effectively modified membrane fouling pathways and improved long-term operational stability. Our findings showed that the combined application of abrupt reciprocation, biogas scouring, and quorum quenching exhibited strong synergistic effects in mitigating membrane fouling and supporting sustainable AnMBR operation.

Keywords: anaerobic membrane bioreactor; membrane fouling; quorum quenching; reciprocation; transmembrane pressure; fouling resistance; Hermia model; PCA

1. Introduction

In the pursuit of sustainable wastewater management, the development of technologies that facilitate both high-quality water reclamation and resource recovery has become a global priority. Anaerobic Membrane Bioreactors (AnMBRs) have emerged as a leading solution, offering distinct advantages, including methane-rich biogas production, a smaller physical footprint, and significantly lower sludge production compared to conventional aerobic processes (Kanwar et al., 2025; Turan, 2025). AnMBRs have attracted increasing attention as advanced wastewater treatment technology due to their ability to simultaneously achieve high-quality effluent, low sludge generation, and renewable energy recovery through methane production (Bajeh et al., 2026; Chen et al., 2016; Lin et al., 2013; Nwachi et al., 2025). Compared with conventional aerobic treatment systems, AnMBRs offer several important advantages, including reduced aeration requirements, lower energy consumption, and enhanced treatment efficiency for high-strength organic wastewater (Ho & Sung, 2010; Smith et al., 2014). Furthermore, integrating membrane filtration with anaerobic digestion enables complete biomass retention, thereby improving sludge retention time (SRT) and enhancing microbial stability under variable operational conditions (Jayabal & Sivanraju, 2025; Martinez-Sosa et al., 2011; Mohidin et al., 2026).

Despite these advantages, membrane fouling remains one of the major limitations restricting the widespread application of AnMBRs. Membrane fouling leads to rapid permeate flux decline, transmembrane pressure (TMP) increases operational costs, and shortens membrane lifespan (Attia et al., 2026; Jiang et al., 2026; Turan, 2025). Fouling in AnMBRs is a highly complex phenomenon involving interactions among suspended solids, extracellular polymeric substances (EPS), soluble microbial products (SMPs), colloidal particles, and microbial biofilms (Franci Gonçalves et al., 2025; Li et al., 2022; Sun et al., 2024). Previous studies have demonstrated that anaerobic sludge generally contains higher concentrations of SMPs and fine colloids than aerobic sludge, thereby making AnMBRs particularly susceptible to severe membrane fouling (Chen et al., 2016; Lin et al., 2012).

Membrane fouling mechanisms in submerged AnMBRs are commonly classified into pore blocking, cake layer formation, adsorption, and irreversible biofouling (Annop et al., 2014; Guo et al., 2022; Zhou et al., 2019). Among these mechanisms, irreversible fouling caused by microbial attachment and biofilm maturation is considered the most critical, as it cannot be

effectively removed by simple physical cleaning (Hebishy et al., 2024; Maillard & Centeleghe, 2023). The accumulation of EPS and SMPs on membrane surfaces can significantly accelerate the development of fouling by promoting the formation of a compact cake layer and pore constriction (Khan et al., 2025). Moreover, elevated hydraulic loading and excessive permeation flux have been reported to intensify foulant deposition and TMP accumulation due to increased convective transport of colloidal materials toward membrane surfaces (Robles et al., 2012; Xiong et al., 2016).

Various physical, chemical, and biological approaches have therefore been developed to mitigate membrane fouling in AnMBR systems. Conventional physical anti-fouling strategies include gas scouring, backwashing, vibration, and hydrodynamic turbulence enhancement (Gheraout, 2018). Among these approaches, mechanical reciprocation has recently gained attention for effectively improving hydrodynamic shear stress near membrane surfaces and suppressing foulant deposition without excessive chemical consumption. Enhanced hydrodynamic conditions generated by membrane movement can disrupt cake layer formation and maintain membrane permeability during long-term operation (Jeison & Vanlier, 2007; Li et al., 2022). However, excessive turbulence may also destabilize sludge flocs, increase SMP release, and aggravate pore blocking phenomena. Therefore, optimization of hydrodynamic conditions remains critically important for sustainable membrane operation.

In recent years, quorum quenching (QQ) has emerged as a promising biological anti-biofouling strategy for membrane bioreactor systems (Afroze et al., 2026; Ganaraja & Mulky, 2024; Roy et al., 2026). Quorum sensing is a microbial communication mechanism regulated by signaling molecules such as acyl-homoserine lactones (AHLs), which control biofilm formation and EPS secretion. Quorum quenching interferes with these signaling pathways and suppresses microbial communication, thereby reducing biofilm development and membrane fouling progression (Das et al., 2026; Li et al., 2025). Previous studies have demonstrated that QQ bacteria can effectively mitigate biofouling in membrane bioreactors by inhibiting EPS production and weakening biofilm structural integrity (Gheraout, 2018; Liu et al., 2019). Moreover, the integration of QQ with physical cleaning strategies has been shown to produce synergistic anti-fouling effects and significantly improve membrane operational stability (Waheed et al., 2020; Weerasekara et al., 2014).

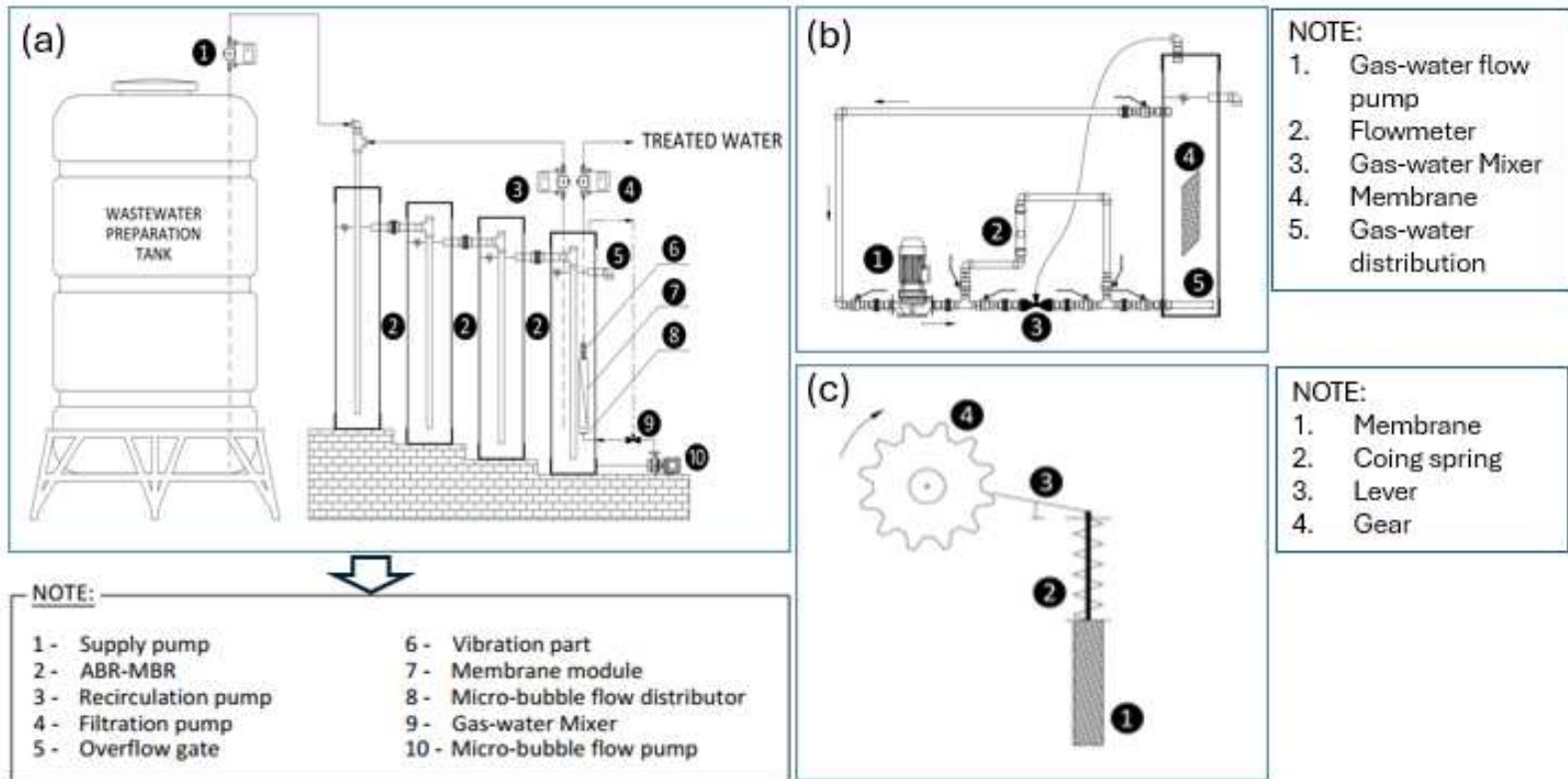
Although numerous studies have investigated physical and biological anti-fouling approaches individually, limited information is currently available regarding the combined effects of mechanical reciprocation, biogas scouring, and quorum quenching on membrane fouling behavior in anaerobic membrane bioreactors. In particular, the interactions between hydrodynamic shear enhancement and biological biofilm suppression mechanisms remain insufficiently understood. Furthermore, the evolution of fouling resistance components and their relationships with hydraulic performance under integrated anti-fouling conditions have not been comprehensively investigated.

Therefore, this study investigates the comprehensive performance and fouling mitigation of a 45-liter, 3-compartment AnMBR system. The primary objectives are: (i) to characterize the organic removal efficiency (COD and BOD) during the critical system startup phase; (ii) to quantify the impact of different flux levels on natural flowrate degradation; and (iii) to evaluate the synergistic effects of combining abrupt reciprocation, biogas microbubble scouring, and QQ microorganisms (*Bacillus*, *Rhodopseudomonas*). By conducting a detailed analysis of the distribution of resistance, this research aims to develop a scalable model to reduce irreversible membrane fouling and enhance the long-term stability of anaerobic wastewater treatment systems.

2. Materials and methods

2.1. Anaerobic membrane bioreactor configuration

The experimental system consisted of a laboratory-scale anaerobic membrane bioreactor (AnMBR) configured as an anaerobic migrating bed reactor (AMBR) integrated with a submerged membrane module (**Fig. 1**). The reactor was divided into three compartments to enhance sludge retention and improve the efficiency of anaerobic degradation. Each compartment had a diameter of 168 mm and a height of 800 mm, with a working hydraulic volume of approximately 45 L. A flat-sheet membrane module was installed inside the reactor for solid–liquid separation. The membrane sheet dimensions were 100 × 100 mm with an effective filtration area of 0.02 m². The reactor was operated under an upflow velocity of 0.5 m h⁻¹ to maintain biomass suspension and improve substrate contact. Biogas generated during anaerobic digestion was simultaneously utilized for membrane scouring to minimize foulant accumulation on membrane surfaces.



122 **Fig. 1.** Schematic diagrams of the ABR-MBR system and membrane fouling-control
 123 configurations: (a) basic ABR-MBR system, (b) microbubble-based system, and (c) vibration-
 124 assisted membrane system.

2.2. Reactor startup and operational conditions

The reactor startup phase was conducted over 17 weeks to establish stable anaerobic microbial activity and acclimatize sludge biomass to the operational conditions. During startup, temporal variations in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were monitored to evaluate reactor stabilization and organic matter removal efficiency. The reactor was continuously operated under anaerobic conditions throughout the experimental period. After successful startup, membrane filtration experiments were performed under different imposed fluxes of 100, 200, and 400 LMH to investigate the effects of hydraulic loading on membrane fouling behavior. Permeate flow rate and transmembrane pressure (TMP) were continuously monitored during operation to evaluate hydraulic performance and fouling progression.

2.3. Membrane fouling experiments under different hydraulic fluxes

Membrane fouling behavior was evaluated under three operational fluxes (100, 200, and 400 LMH). Permeate flow rate decline was monitored over a 48-h filtration period to assess hydraulic deterioration under different membrane loading conditions. The evolution of fouling was analyzed using Hermia fouling models to identify the dominant mechanisms of membrane fouling during filtration. Four classical Hermia mechanisms, including complete pore blocking, standard pore blocking, intermediate pore blocking, and cake filtration, were evaluated based on permeate flux decline behavior.

The total membrane resistance was calculated according to Darcy's law:

$$J = \frac{\Delta P}{\mu R_t}$$

where:

- J = permeate flux ($\text{m}^3 \text{m}^{-2} \text{h}^{-1}$),
- ΔP = transmembrane pressure (TMP)
- μ = dynamic viscosity of the permeate ($\text{Pa}\cdot\text{s}$)
- R_t = total filtration resistance (m^{-1})

The total resistance was further partitioned into intrinsic membrane resistance, cake resistance, pore blocking resistance, and irreversible resistance according to:

$$R_t = R_m + R_c + R_p + R_{ir}$$

where R_m , R_c , R_p , and R_{ir} represent intrinsic membrane resistance, cake layer resistance, pore blocking resistance, and irreversible fouling resistance, respectively.

2.4. Mechanical reciprocation and anti-fouling strategies

Abrupt reciprocation was applied as a physical anti-fouling strategy to improve hydrodynamic shear stress near the membrane surface. Reciprocation frequencies ranging from 0 to 600 Hz were investigated to determine the optimal operating condition for mitigating membrane fouling. The hydraulic performance of the membrane system was evaluated after 24 h of operation at different reciprocation frequencies by measuring permeate flow rate. In addition to mechanical reciprocation, integrated anti-fouling strategies combining biogas scouring with quorum-quenching (QQ) microorganisms were investigated. *Bacillus* spp. and *Rhodopseudomonas* spp. were used as quorum-quenching bacteria to suppress microbial communication pathways associated with biofilm formation and extracellular polymeric substance (EPS) secretion. Comparative experiments were conducted between the control system and the integrated QQ-assisted system over 10 days of operation. Temporal variations in flow rate, TMP, and fouling resistance components were monitored to evaluate anti-fouling efficiency.

2.5. Fouling resistance analysis

Membrane fouling resistance was classified into cake resistance, pore-blocking resistance, and irreversible resistance to evaluate fouling characteristics under different operating conditions. TMP and permeate flow rate data were used to calculate individual resistance contributions throughout the experimental period. The percentage contribution of each fouling component to total membrane resistance was determined to identify dominant fouling mechanisms. The transition between reversible and irreversible fouling behaviors was further analyzed by examining changes in the distribution of resistance under control and quorum-quenching conditions.

2.6. Statistical and multivariate analysis

All statistical analyses and graphical visualizations were performed using R software version 4.5.3 (R Foundation for Statistical Computing, Vienna, Austria). Principal component analysis (PCA) was conducted to evaluate the relationships among membrane hydraulic performance, TMP evolution, and fouling resistance components under different operational conditions. Correlation network analysis was additionally employed to investigate the interconnectivity among fouling-related parameters. Hermia fouling models were fitted using nonlinear regression analysis to identify dominant membrane fouling mechanisms during filtration. Independent

samples t-tests were performed to compare membrane fouling parameters between the control and quorum-quenching treatments. Experimental data were expressed as mean $\pm$ standard deviation. Statistical significance was considered at $p < 0.05$.

3. Results and discussions

3.1. Start-up performance of the AnMBR system

The start-up performance of the anaerobic membrane bioreactor (AnMBR) was evaluated over a 17-week operational period based on temporal variations in COD and BOD concentrations (**Fig. 2**). Both organic parameters gradually decreased throughout the acclimatization phase, indicating successful establishment of anaerobic microbial activity and stabilization of reactor performance. Initially, the reactor exhibited relatively high organic concentrations, with influent BOD and COD values of 1014 and 1268 mg/L, respectively. After 17 weeks of operation, the concentrations decreased to 236 and 393 mg/L, corresponding to reductions of approximately 76.7% and 69.0%, respectively. The gradual reduction in organic matter suggested progressive adaptation of anaerobic microbial consortia and stabilization of methanogenic pathways.

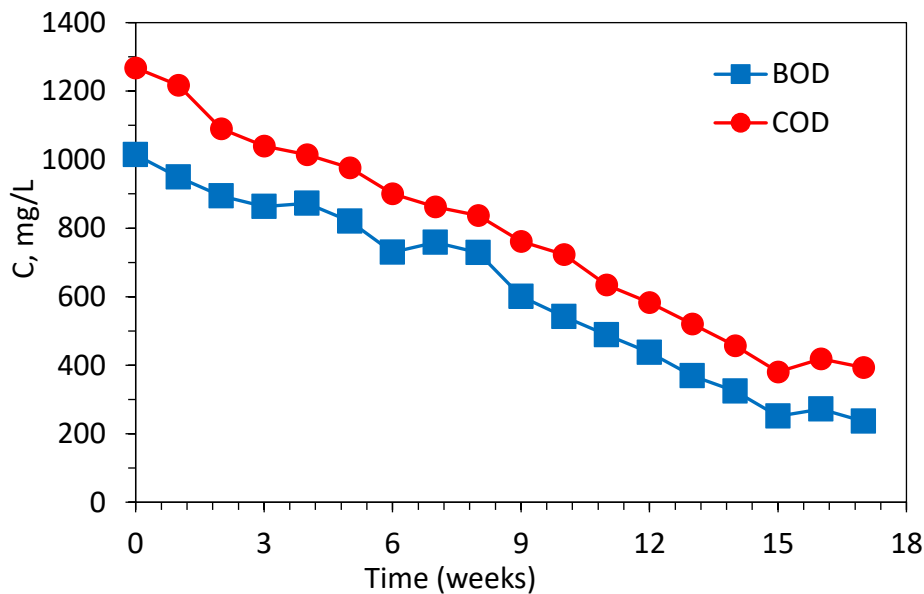


Fig. 2. Temporal variations in COD and BOD removal performance during the 17-week startup phase of the AnMBR

During the initial operational stage (weeks 0–6), the reduction rates remained relatively moderate, likely due to slow microbial acclimatization and biomass enrichment. Similar startup

behavior has been widely reported in submerged AnMBR systems treating high-strength wastewater, where methanogenic microorganisms require extended adaptation periods before stable degradation performance can be achieved (Lin et al., 2013; Martinez-Sosa et al., 2011). From week 8 onward, more pronounced reductions in both COD and BOD concentrations were observed, indicating enhanced hydrolysis and methanogenic activity. A slight increase in COD concentration was observed at week 16, which may be associated with temporary sludge detachment or fluctuations in microbial metabolism. Similar transient instabilities during biomass restructuring have previously been reported in anaerobic systems under dynamic operational conditions (Chen et al., 2016; King & King, 2026; Tiron et al., 2026; Wyss et al., 2026). Nevertheless, the overall downward trend confirmed stable reactor startup and successful acclimatization prior to membrane fouling experiments. Stable anaerobic activity is critically important because unstable biomass conditions can increase the production of soluble microbial products (SMPs) and extracellular polymeric substances (EPS), both of which strongly contribute to the development of membrane fouling (Li et al., 2026; Vydehi et al., 2025; Yan et al., 2026). Therefore, the stable startup performance observed in this study contributed to the subsequent membrane operational stability.

3.2. Flux-dependent membrane fouling behavior

Fig. 3 presents the temporal evolution of permeate flow rate under different imposed membrane fluxes (100, 200, and 400 LMH). Membrane fouling became increasingly severe with increasing hydraulic loading intensity. At the highest flux of 400 LMH, the permeate flow rate declined rapidly from 60.3 to 16.0 mL/min within 48 h, representing a reduction of approximately 73.5%. In contrast, lower flux conditions exhibited relatively slower hydraulic deterioration.

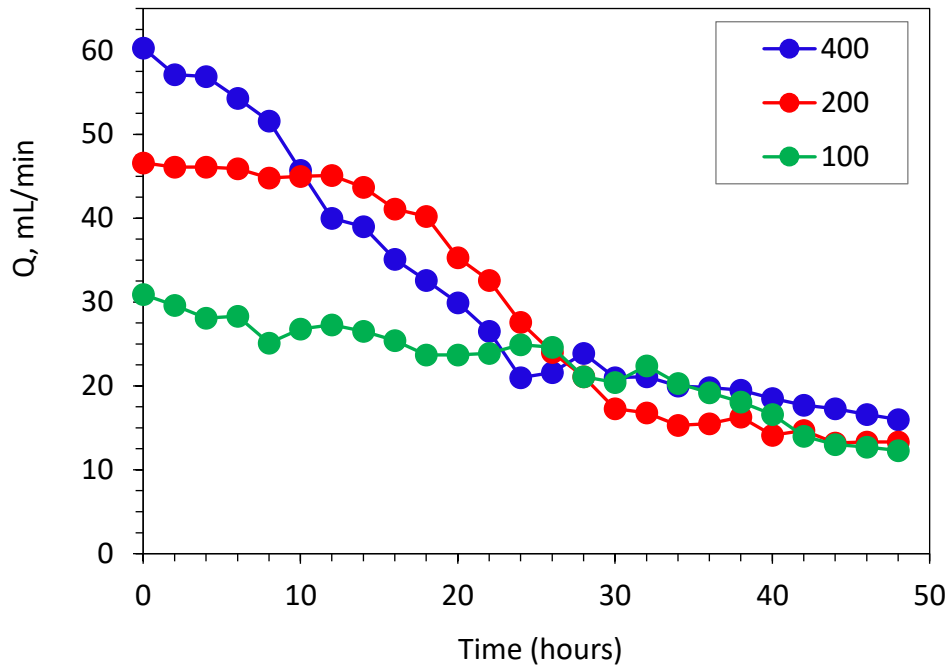
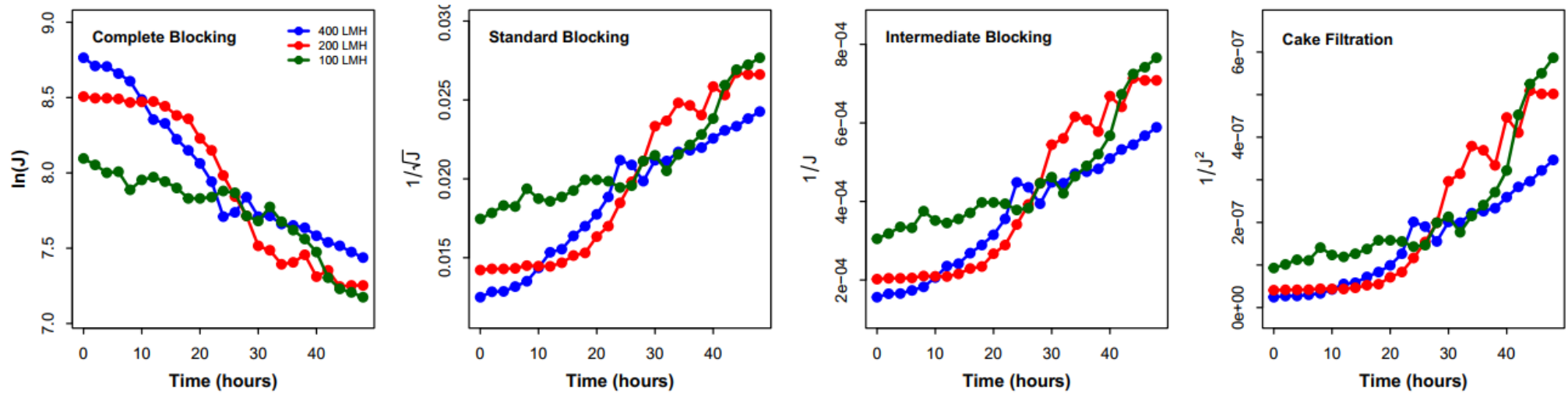


Fig. 3. Flowrate degradation profiles over 48 hours under various operational fluxes (100, 200, and 400 LMH)

The severe flux decline observed at 400 LMH indicated accelerated foulant accumulation and enhanced membrane resistance under excessive permeation conditions. High hydraulic loading generally increases convective transport of suspended solids, colloidal particles, SMPs, and EPS toward the membrane surface, thereby promoting rapid cake layer formation and pore obstruction (Khan et al., 2025; Turan, 2025). A distinct two-stage fouling pattern was observed during filtration. In the initial stage, a rapid decline in flow rate suggested dominant pore blocking and adsorption phenomena caused by the penetration of fine particles into the membrane pores. Subsequently, the decline rate slowed, indicating a transition toward cake layer-controlled filtration resistance. Similar fouling evolution has frequently been reported in anaerobic membrane systems and is consistent with classical Hermia fouling mechanisms (Aghili Dehnavi et al., 2023; Lin et al., 2014; Silva et al., 2026; Xiong et al., 2016).

241



242 **Fig. 4.** Hermia model-based fouling kinetics revealing the transition from pore blocking to cake layer formation under increasing
 243 hydraulic loading conditions.

The Hermia kinetic analysis presented in **Fig. 4** further confirmed that intermediate blocking dominated during the early filtration stage, whereas cake filtration became the dominant fouling mechanism during prolonged operation. Similar transitions have been observed in submerged membrane bioreactors, where continuous deposition of microbial flocs and EPS progressively forms compact cake layers on membrane surfaces (Cao et al., 2018; Ou et al., 2010; Xiao et al., 2024). The relatively stable hydraulic performance observed at 100 LMH suggested that operating below the critical flux can effectively delay the development of fouling and maintain membrane permeability. Similar findings were reported by Robles et al. (2012), who demonstrated that subcritical flux operation significantly prolongs membrane lifespan and reduces the frequency of membrane cleaning in industrial-scale AnMBRs. These findings clearly demonstrate that excessive hydraulic loading significantly accelerates membrane fouling and reduces the sustainability of filtration.

3.3. Optimization of abrupt reciprocation frequency

The influence of abrupt reciprocation frequency on membrane hydraulic performance after 24 h of operation is presented in **Fig. 5**. The implementation of reciprocation substantially improved membrane productivity compared with the non-reciprocating condition. Without reciprocation, the flow rate decreased to only 21.0 mL/min after 24 h. In contrast, moderate reciprocation frequencies significantly enhanced hydraulic performance, with the highest flow rate of 51.5 mL/min observed at 30 Hz.

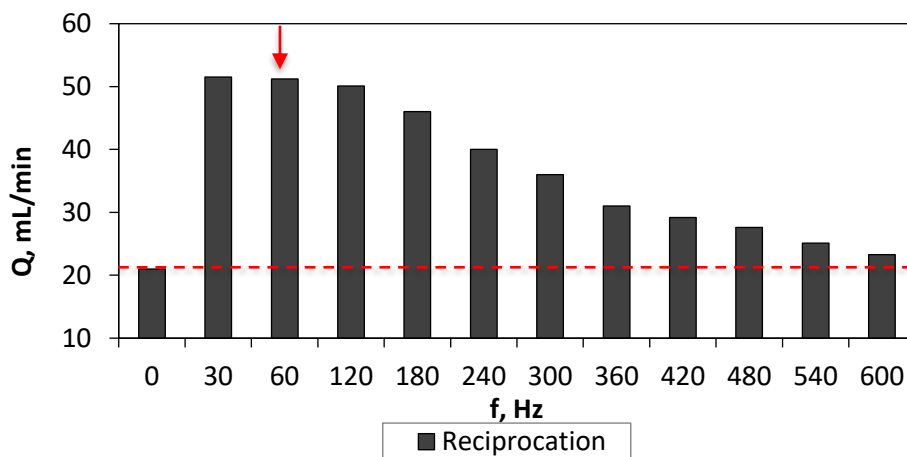


Fig. 5. Impact of mechanical reciprocation frequency on hydraulic productivity after 24 hours of operation

The improved membrane productivity can be attributed to enhanced hydrodynamic shear stress generated by abrupt reciprocation, which reduced foulant deposition and weakened cake layer consolidation on the membrane surface. Mechanical disturbance likely disrupted loosely attached foulants and suppressed the formation of dense fouling structures, thereby maintaining higher membrane permeability. However, increasing reciprocation frequency beyond 60 Hz resulted in gradual hydraulic deterioration. At frequencies above 240 Hz, the flow rate decreased continuously, reaching only 23.3 mL/min at 600 Hz. Excessive reciprocation may destabilize sludge flocs and promote fragmentation into smaller particles that can more easily penetrate membrane pores, thereby intensifying internal fouling. Similar observations were reported by Lin et al. (2012), who found that excessive turbulence increased SMP release and accelerated pore blockage. In addition, extremely high reciprocation frequencies may substantially increase energy consumption without proportional improvements in fouling mitigation efficiency. Therefore, moderate reciprocation frequencies (30~60 Hz) appear to provide optimal hydrodynamic conditions for balancing membrane cleaning efficiency and operational stability. These findings demonstrated that controlled mechanical reciprocation can serve as an effective physical anti-fouling strategy to improve the sustainability of membrane filtration in AnMBR systems.

3.4. Effects of integrated anti-fouling strategies on hydraulic performance

Fig. 6 compares the hydraulic performances of the control system and the integrated quorum quenching (QQ)-assisted system during 10 days of membrane operation. Both systems exhibited a gradual decline in flow rate over time; however, the QQ-assisted reactor maintained substantially greater hydraulic stability throughout the experimental period.

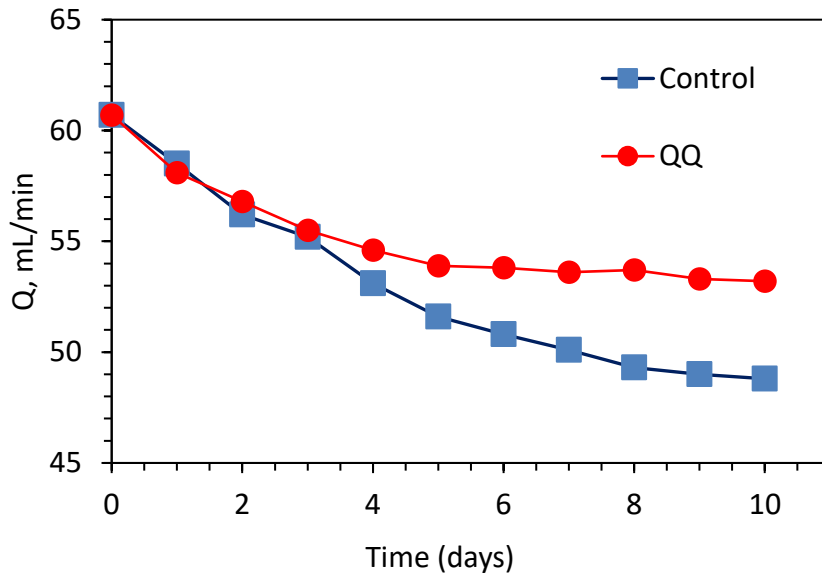


Fig. 6. Comparative analysis of flow rate degradation and transmembrane pressure (TMP) under mechanical and synergistic (mechanical + QQ) anti-fouling strategies.

In the control system, the permeate flow rate decreased from 60.7 to 48.8 mL/min after 10 days, whereas the QQ-assisted system maintained a higher final flow rate of 53.2 mL/min. The slower hydraulic deterioration observed under QQ-assisted conditions demonstrated the effectiveness of quorum quenching in suppressing membrane fouling. Quorum quenching microorganisms interfere with quorum-sensing signaling molecules such as acyl-homoserine lactones (AHLs), thereby inhibiting microbial communication pathways associated with EPS secretion and biofilm maturation (Bouayed et al., 2016; Güneş & Taşkan, 2022; Jiang et al., 2013; Liu et al., 2019; Oh et al., 2012). Similar anti-biofouling effects have been reported by (Liu et al., 2019), who demonstrated that quorum quenching significantly prolonged membrane operational duration and delayed TMP accumulation in anaerobic membrane bioreactors. The combined application of abrupt reciprocation, biogas scouring, and quorum quenching generated synergistic anti-fouling effects. Mechanical reciprocation and gas scouring primarily controlled reversible cake layer deposition by enhancing hydrodynamic shear, whereas quorum quenching suppressed the formation of biologically induced irreversible fouling. Similar synergistic interactions between physical cleaning and biological anti-biofouling strategies have previously been reported in membrane bioreactor systems (Waheed et al., 2020; Weerasekara et al., 2014). Suppression of EPS secretion likely weakened foulant cohesion and reduced the formation of compact biofilm structures. Consequently, membrane foulants became more loosely attached and easier to remove through physical scouring processes. These findings strongly suggested that integrated physical-

biological anti-fouling strategies can effectively enhance the long-term operational stability of AnMBR.

3.5. Evolution of transmembrane pressure and fouling resistance distribution

The temporal evolution of transmembrane pressure (TMP) and fouling resistance components under control and QQ-assisted conditions is shown in **Fig. 7**.

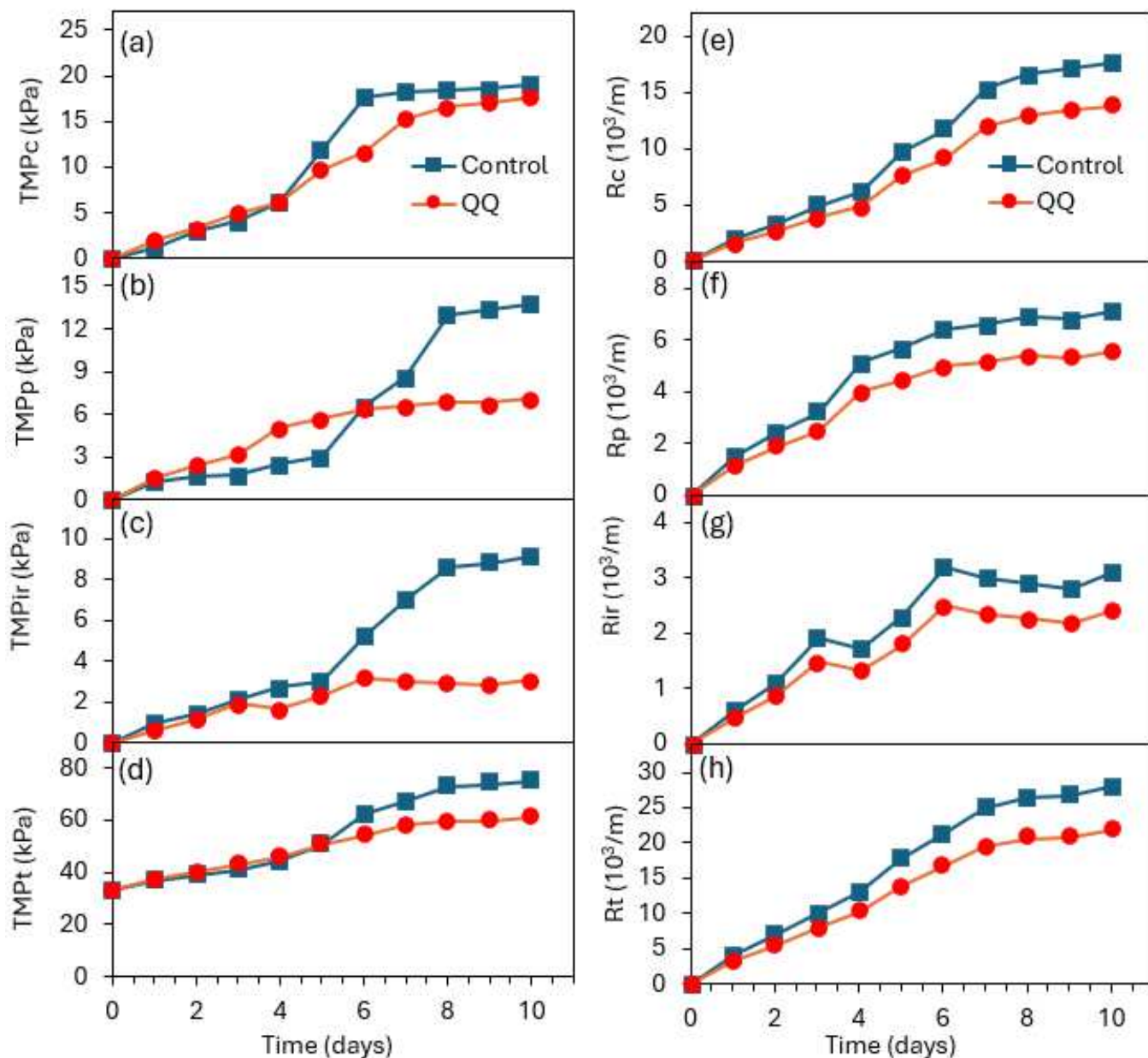


Fig. 7. Temporal evolution of transmembrane pressure (a-d) and fouling resistance components (e-h) under integrated mechanical and Quorum Quenching (QQ) strategies.

It is shown clearly that TMP increased continuously in both systems during operation, indicating progressive membrane fouling. However, the QQ-assisted reactor exhibited substantially lower TMP accumulation compared with the control system. At day 10, the total TMP of the control system reached 74.9 kPa, whereas the QQ-assisted system maintained a lower TMP of 60.9 kPa. The reduced TMP growth rate indicated that quorum quenching effectively delayed the buildup of membrane resistance and suppressed the development of severe biofouling. Detailed resistance analysis revealed substantial differences in fouling composition between the two operational strategies. In the control system, cake resistance, pore resistance, and irreversible resistance accounted for approximately 45.6%, 32.7%, and 21.7% of total fouling resistance, respectively. In contrast, the QQ-assisted system exhibited resistance contributions of 63.4%, 25.4%, and 11.1%, respectively. The significant reduction in irreversible resistance under QQ-assisted conditions strongly suggested suppression of compact biofilm formation and internal pore clogging (Biswas et al., 2021; Carballeira Braña et al., 2021). Since irreversible fouling is generally difficult to remove by physical cleaning, reducing this fouling fraction is critical for long-term membrane sustainability. Similar reductions in irreversible fouling have been reported in QQ-assisted membrane systems, where microbial signaling pathways were effectively disrupted (Güneş & Taşkan, 2022; Liu et al., 2019). Interestingly, the larger contribution of cake resistance in the QQ-assisted system indicated that membrane fouling became more reversible and physically removable. Similar transformations from irreversible to reversible fouling behavior have previously been observed in membrane systems employing quorum quenching strategies (Xu et al., 2020). Previous studies have demonstrated that irreversible fouling is strongly associated with EPS accumulation and microbial adhesion inside membrane pores (Le-Clech et al., 2006; Meng et al., 2009). Therefore, the substantial reduction in irreversible resistance observed in this study confirmed that quorum quenching effectively altered membrane fouling characteristics and improved fouling reversibility.

3.6. Multivariate analysis of membrane fouling behavior

The principal component analysis (PCA) biplot shown in **Fig. 8** revealed clear distinctions between control and QQ-assisted operational conditions. The control samples were strongly associated with total resistance, irreversible resistance, and TMP accumulation, indicating severe progression of membrane fouling. In contrast, the QQ-assisted samples clustered more closely under stable flow-rate conditions and with lower resistance accumulation.

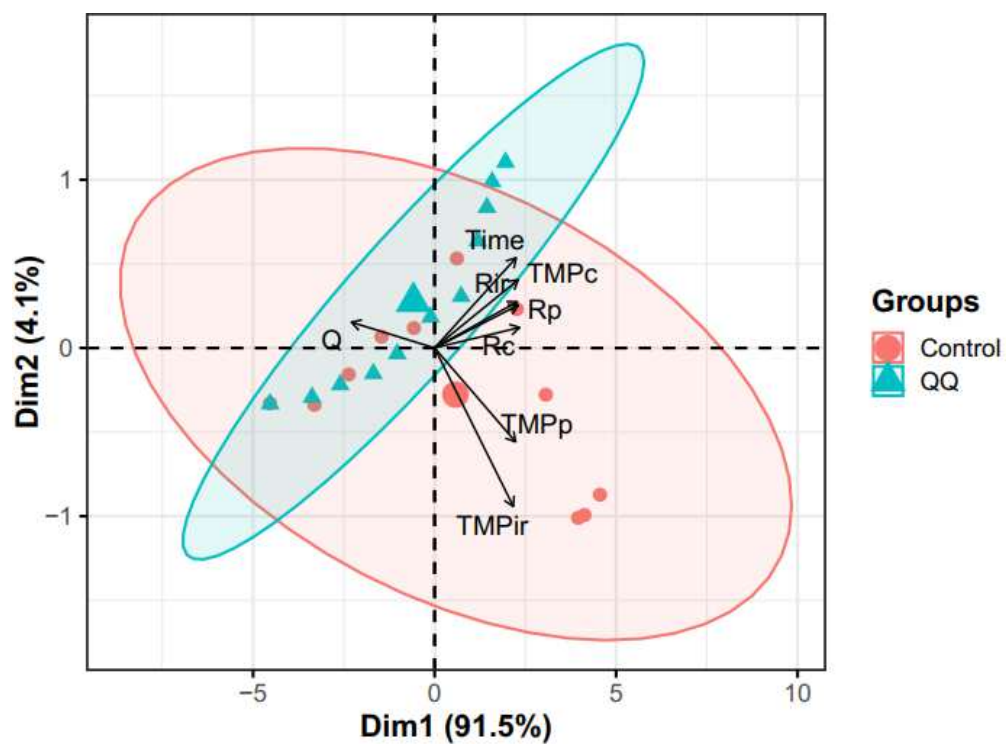


Fig. 8. Principal component analysis (PCA) biplot of membrane fouling behavior under Control and QQ treatments

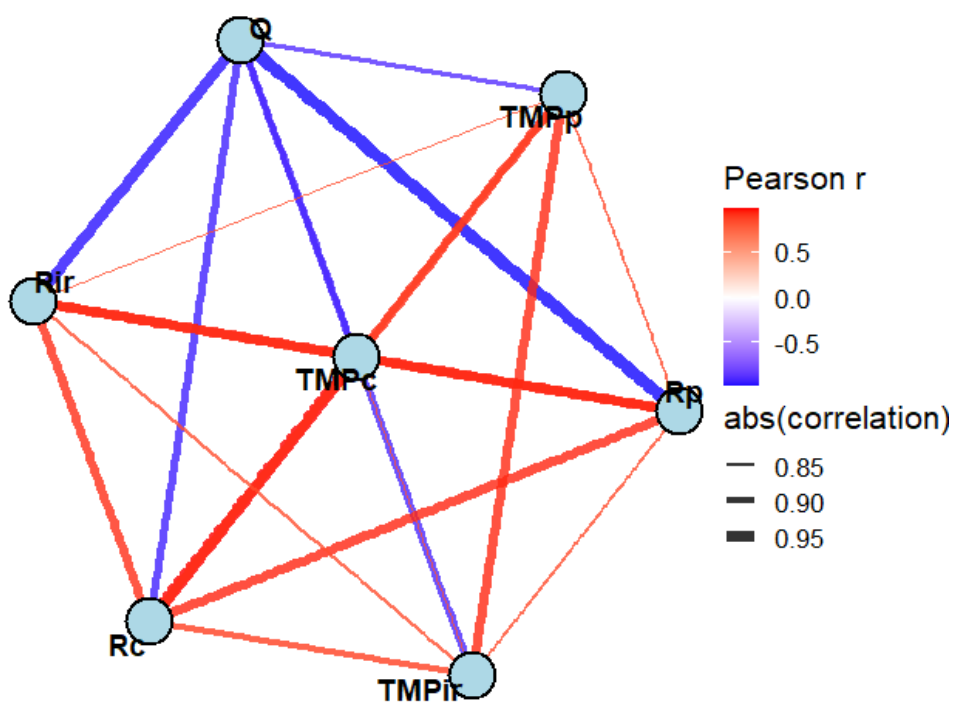


Fig. 9. Correlation network analysis revealing the interconnectivity among permeate flux, fouling resistances, and transmembrane pressure components

The PCA results suggested that irreversible fouling and TMP growth were the dominant factors governing hydraulic deterioration in the control system. Similar relationships between EPS accumulation, irreversible fouling, and TMP increase have been widely reported in membrane bioreactor studies (Cosenza et al., 2013; Le-Clech et al., 2006; Liu et al., 2012; Turan, 2025). The correlation network analysis presented in **Fig. 9** further demonstrated strong interconnectivity among permeate flow rate, TMP, and fouling resistance components. Negative correlations were observed between permeate flow rate and total membrane resistance, whereas TMP exhibited strong positive correlations with irreversible and pore resistance components. These findings confirmed that irreversible fouling played a dominant role in long-term hydraulic deterioration. Similar relationships have previously been identified in submerged membrane systems, where biofilm-associated fouling significantly contributed to membrane resistance buildup (Cosenza et al., 2013; Phillip et al., 2026; Sharma et al., 2026). Therefore, the multivariate analyses confirmed that integrated anti-fouling strategies combining mechanical reciprocation, biogas scouring, and quorum quenching substantially modified membrane fouling pathways and improved long-term AnMBR filtration stability.

4. Conclusion

This study demonstrated that integrated anti-fouling strategies involving abrupt reciprocation, biogas scouring, and quorum quenching effectively improved the hydraulic stability of the membrane in an anaerobic membrane bioreactor. The reactor achieved stable startup performance, with significant reductions in COD and BOD during the 17-week acclimatization period. High hydraulic loading accelerated membrane fouling, with Hermia model analysis revealing a transition from pore-blocking to cake-layer-dominated fouling. Moderate reciprocation frequencies (30 - 60 Hz) significantly enhanced membrane performance by improving hydrodynamic shear and reducing foulant accumulation. Compared with the control system, the QQ-assisted reactor maintained a higher permeate flow rate, lower TMP accumulation, and substantially reduced irreversible fouling resistance. PCA and correlation network analyses further confirmed that the integrated anti-fouling strategies effectively altered membrane fouling pathways and improved long-term operational stability. Our results confirmed that the combined application of mechanical reciprocation, biogas scouring, and quorum quenching represents a promising approach for sustainable fouling mitigation and long-term AnMBR operation.

Contribution statement

Tran Minh Thao: Conceptualization, Methodology, Investigation, Data curation, Writing original draft. Do Hong Hanh: Investigation, Validation, Formal analysis, Visualization. Nguyen Hoang Phuc Son: Investigation, Software, Resources, Data curation. Toan Nguyen-Sy: Conceptualization, Supervision, Project administration, Funding acquisition, Writing review & editing. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research is funded by Funds for Science and Technology Development of the University of Danang under project number B2025-DN06-11.

Statements and Declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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