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Phosphorus removal in membrane bioreactor systems: a systematic review of operational parameters and configurations

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Abstract

Phosphorus (P) is an essential yet finite resource, and concerns about its availability are intensified by population growth, urbanization, and increasing food demand, while stringent discharge regulations are required to protect aquatic ecosystems from eutrophication. Membrane bioreactors (MBRs) combine biological treatment with membrane separation, enabling high effluent quality and supporting water reuse; however, the literature reports P performance in ways that are difficult to compare across studies. This systematic review screened 854 Scopus records (2014–2025) and synthesized 29 eligible bench- and pilot-scale studies reporting at least one operational parameter (transmembrane pressure (TMP), hydraulic retention time (HRT), sludge retention time (SRT), or aeration) alongside P performance. Its novelty lies in linking operational settings to performance separately for each P fraction, distinguishing true dissolved-P removal from particulate retention by the membrane, a distinction rarely made in earlier reviews. High total phosphorus (TP) removals (>90%) were frequently reported under optimized or hybrid conditions, including electro-assisted configurations such as electrocoagulation, whereas conventional aerobic MBRs showed more variable orthophosphate removal. Operational settings that improve biological uptake or promote precipitation enhanced P removal but also intensified fouling, revealing a consistent

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trade-off between effluent quality and membrane service life. The evidence supports MBR-based systems as a versatile platform for meeting stringent P targets, provided that P fractions are reported explicitly and that removal mechanisms are separated from solids retention.

Keywords: Nutrient recovery; Wastewater treatment; Biological degradation; Scientometric analysis; Sustainability.

Remoção de fósforo em sistemas de biorreatores com membranas: uma revisão sistemática de parâmetros operacionais e configurações

Resumo
O fósforo (P) é um recurso essencial, porém finito, e as preocupações com sua disponibilidade são intensificadas pelo crescimento populacional, pela urbanização e pela demanda por alimentos, enquanto regulamentações rigorosas de lançamento protegem os ecossistemas aquáticos da eutrofização. Os biorreatores com membranas (MBRs) combinam tratamento biológico e separação por membranas, possibilitando elevada qualidade do efluente e o reúso da água; contudo, o desempenho quanto ao P é relatado de formas dificilmente comparáveis entre estudos. Esta revisão sistemática analisou 854 registros da base Scopus (2014–2025) e sintetizou 29 estudos elegíveis em escala de bancada e piloto que reportaram ao menos um parâmetro operacional (pressão transmembrana (TMP), tempo de retenção hidráulica (HRT), tempo de retenção de lodo (SRT) ou aeração) juntamente com o desempenho relacionado ao P. Sua contribuição original está em associar condições operacionais ao desempenho separadamente para cada fração de P, distinguindo a remoção efetiva de P dissolvido da retenção de particulado pela membrana, distinção rara em revisões anteriores. Elevadas remoções de fósforo total (TP) (>90 %) foram relatadas sob condições otimizadas ou híbridas, incluindo configurações assistidas eletroquimicamente, como a eletrocoagulação, enquanto MBRs aeróbios convencionais apresentaram remoção mais variável de ortofosfato. Configurações que favorecem a absorção biológica ou a precipitação aumentaram a remoção de P, mas intensificaram a colmatação, evidenciando um compromisso entre qualidade do efluente e vida útil das membranas. As evidências sustentam os sistemas baseados em MBR como plataforma versátil para atender metas rigorosas de P, desde que as frações de fósforo sejam reportadas explicitamente.

Palavras-chave: Recuperação de nutrientes; Tratamento de águas residuárias; Degradação biológica; Análise cienciométrica; Sustentabilidade.

1 Introduction

Phosphorus (P) is an essential element for all living organisms. However, the primary supply of this element is derived from nonrenewable phosphate rock resources (Lin et al., 2024). The increasing demand for food has led to a greater reliance on P in agricultural practices, which has raised concerns about the long-term sustainability of resource availability (He et al., 2023). Concurrently, the implementation of more stringent regulations on P discharge has been undertaken with the objective of mitigating eutrophication and other environmental impacts associated with excess P in aquatic systems (Jin et al., 2024).

Wastewater contains both organic and inorganic P fractions (e.g., phospholipids, phosphate esters, apatite, and iron phosphate), which motivates targeted treatment approaches (Carrillo et al., 2020). The degree of reported P removal in conventional wastewater treatment plants can exhibit significant variability, contingent on process design and operating conditions. In numerous instances, supplementary measures are necessary to adhere to more stringent discharge limits (Van Vuuren et al., 2010). Precipitation is an effective method; however, it has been observed to result in increased chemical demand and sludge production (Jin et al., 2024). Biological routes exemplified by enhanced biological phosphorus removal, are appealing from a sustainability perspective. However, their effectiveness is contingent upon operational conditions and influent characteristics (Faria et al., 2006).

Three bodies of evidence frame this review. First, operational parameters govern P performance: HRT and SRT set the balance between anaerobic release and aerobic uptake by phosphorus-accumulating organisms (PAOs), aeration controls both oxygen supply and shear-driven fouling control, and TMP reflects the accumulation of material on the membrane surface. Recent syntheses show that these parameters are rarely reported in a comparable manner across studies, which limits meta-analytical treatment of the evidence base (Saidulu et al., 2021). Second, MBR configurations have diversified well beyond the submerged/sidestream dichotomy, now encompassing multi-zone biological trains, biofilm-assisted hybrids, granular sludge systems, and electro-assisted arrangements; each imposes a different balance between nutrient performance and membrane service life (Khoiruddin et al., 2025). Third, fouling remains the dominant operational constraint, and the strategies that most improve P removal (higher biomass concentrations, coagulant dosing, and chemical precipitation within the reactor) are frequently the same strategies that accelerate fouling (Turan, 2025).

Membrane bioreactors (MBRs) are a specialized type of wastewater treatment system that integrates biological treatment with membrane separation, resulting in compact footprints and high effluent quality (Sorgato et al., 2023, Zhang et al., 2023). However, it is important to distinguish between (i) improved solids retention by the membrane (which primarily affects particulate-bound P) and (ii) true removal of dissolved P, which depends on biological uptake and/or physicochemical precipitation pathways. Configuration choices (e.g., anaerobic selectors) can promote phosphorus-accumulating organisms and improve biological P removal (Khan et al., 2019).

In municipal wastewater, P occurs as orthophosphate (PO_4^{3-}) and as particulate- and organic-bound fractions. Organic P is often associated with biomolecules, whereas inorganic P may also be present as condensed phosphates (Marguti et al., 2008). To avoid mixing incompatible metrics, P loading is commonly reported either as per-capita mass loads (e.g., g P person^{-1} day^{-1}) or as concentrations (e.g., mg L^{-1}); both perspectives are relevant for design, but they should be interpreted consistently with the underlying assumptions (Andrés et al., 2018).

Despite this expanding literature, three gaps persist. Reported P performance is seldom disaggregated by fraction, so that TP removal attributable to the physical retention of particulate P by the membrane is not separated from the biological or physicochemical removal of dissolved P. Operational conditions are reported heterogeneously, which prevents direct comparison across configurations. And the mechanisms responsible for P removal are frequently asserted rather than examined. Accordingly, this review analyzes the influence of operational parameters and MBR configurations on reported P removal performance, with three specific objectives: (i) to map the evidence base for MBR-based P removal published between 2014 and 2025; (ii) to relate operational parameters to performance separately for each P fraction reported; and (iii) to examine the chemical, physical, and biological mechanisms underlying P removal in MBR systems, including the role of volatile fatty acids (VFAs) and the practical constraints on converting removed P into a recoverable product.

2 Research methodology

This review was based on a systematic literature analysis of P removal using MBR-based systems, as reported in the Scopus database. The search strategy employed a combination of the terms “membrane bioreactor” or “MBR” with “P” or “phosphorus” and the wildcard “remov*”, targeting publications from 2014 to 2025. No restrictions were applied regarding MBR configurations or language.

Scopus was adopted as the single source of records for three reasons. It provides the broadest coverage of peer-reviewed engineering and environmental science journals among the databases with structured export, its metadata fields are internally consistent, which is a precondition for the bibliometric mapping described below, and its export format is natively compatible with VOSviewer, avoiding the record-merging and author-disambiguation errors that arise when heterogeneous exports from multiple databases are combined. The exclusive use of a single database is nevertheless acknowledged as a limitation of this review, since relevant records indexed only in Web of Science, Scopus-excluded regional journals, or grey literature may not have been retrieved. The search window of 2014 to 2025 defines the corpus synthesized in Sections 4.2 and 4.5 and summarized in Tables 1 to 6. Studies published after the search was closed are cited in this review for contextual and mechanistic discussion only; they were not screened against the eligibility criteria, are not included in the 29 eligible studies, and do not appear in the summary tables. Each is identified in the text as falling outside the search window.

The eligibility criteria were defined a priori: (i) original research articles reporting experimental data on P removal in bench and/or pilot-scale MBR-based systems (including hybrid configurations); and (ii) studies reporting at least one operational parameter (e.g., HRT, SRT, TMP, or aeration) in relation to P removal performance. For each included study, we extracted: configuration type, scale, wastewater type, target P fraction (e.g., TP vs. orthophosphate), influent/effluent P concentrations when available, and the reported operating conditions.

Because P fractions are reported inconsistently (e.g., total phosphorus vs. orthophosphate), the results are discussed with explicit reference to the fraction measured. This approach is taken to avoid conflating particulate retention with dissolved P removal.

For the scientometric analysis, VOSviewer (v1.6.20) was employed to identify trends and visualize keyword and country distributions. The filters incorporated a maximum of 25 authors per document, a minimum of 50 citations per document, and a minimum of 50 documents per country.

3 Membrane bioreactor

MBRs are advanced wastewater treatment systems that integrate biological processes with membrane filtration, offering high effluent quality by retaining sludge flocs and macromolecular contaminants (Zhang et al., 2023). Compared to conventional activated sludge systems, MBRs provide advantages such as compact design, low sludge production, simplified operation, and superior pollutant removal efficiency (Judd, 2008, Ravadelli et al., 2021). While typically incorporating aerobic biological treatment and membrane separation in place of secondary clarifiers, anaerobic MBR configurations are also viable (Judd, 2016).

MBRs perform simultaneous biological degradation and physical separation, allowing higher biomass concentrations and enhanced system performance (Guo et al., 2022, Pollice et al., 2004, Zhou et al., 2024). For P removal, MBRs enable sustained microbial activity and improved nutrient removal, often surpassing the performance of conventional treatment plants (Jin et al., 2024, Liu et al., 2022). Their compact and modular design further supports efficient operation and nutrient recovery (Yeon et al., 2005).

3.1 Operational dynamics

MBR technology is recognized for its modularity and adaptability, which provide resilience to load fluctuations and operational flexibility (Cho et al., 2011). MBR systems can be classified by reactor configuration, membrane type and location, and mode of operation. Understanding how operational parameters influence MBR performance is critical, as they directly impact contaminant removal, process stability, and effluent quality.

Commercially, MBRs are implemented in two main configurations: external (sidestream) and submerged (immersed) membrane modules (Andrade et al., 2014, Metcalf & Eddy, 2003). In external configurations, membrane modules are located outside the bioreactor, with two distinct streams: the permeate (treated effluent) and the concentrate (returned to the reactor) (Lens et al., 2015). These systems offer higher hydraulic throughput and operational flexibility but demand greater energy due to elevated TMP, tangential flow velocities, and frequent cleaning cycles (Andrade et al., 2014, Thomas et al., 2000). Nonetheless, they typically require a smaller membrane surface area.

In submerged configurations, membranes are placed directly inside the bioreactor or in a dedicated tank. Suction generated by a vacuum or peristaltic pump on the permeate side enables liquid passage through the membrane, while solids are retained (Liu et al., 2012, Metcalf & Eddy, 2003). Operating under low pressure (typically 0.2–0.8 bar), these systems are energy-efficient and compact, with membrane modules often positioned above aeration units or within separate compartments (Belli et al., 2021).

Membrane materials are broadly categorized into polymeric and ceramic types (Ravadelli et al., 2021). Structurally, membranes comprise a selective surface layer supported by a porous substrate for mechanical strength and high surface porosity (Chen et al., 2020). Durability is essential, as membranes must withstand mechanical stress and resist chemical and thermal degradation caused by cleaning agents, pH shifts, and temperature fluctuations (Meng et al., 2017).

Recent developments have expanded this materials landscape. Ceramic membranes, historically constrained by capital cost, have received renewed attention for their chemical and thermal stability and lower fouling propensity, and have been applied in gravity-driven and functional-particle-enhanced MBR configurations achieving simultaneous nitrogen and phosphorus removal (Nie et al., 2023, Qin et al., 2024). Surface modification and the incorporation of functional materials have been pursued to render membrane surfaces less prone to biofilm attachment, while electroactive and electrically conductive membranes allow the membrane itself to act as an electrode, coupling fouling mitigation with electrochemically assisted P removal in a single element (Hu et al., 2024). Gravity-driven configurations, which operate without a suction pump, have likewise been reported to sustain nutrient removal at substantially reduced energy demand (Du et al., 2025). These developments are relevant to P removal because the material and surface properties that resist fouling also determine how much chemical or electrochemical dosing a system can tolerate before membrane performance degrades.

Evidence published after the close of the search window indicates that the trade-off between phosphorus performance and membrane fouling is not as rigid as the earlier literature suggested. Wu et al. (2026) combined a powder carrier with a hydrocyclone to develop micro-granular sludge within an MBR, reporting effluent TP below 0.03 mg L^{-1} together with transmembrane pressure held at approximately 8 kPa for more than 20 days at a flux of 20 L m^{-2} h^{-1}, and achieving this at a short HRT of 6 h and an unfavorable influent C/N ratio of about 3.2. The mechanism reported is indirect: the powder carrier modulates quorum sensing and reduces EPS production, so that fouling is mitigated through the microbial route rather than by hydraulic means. Configurations coupling photosynthetic and heterotrophic biomass have also been described, including internal circulating photogranular reactors (Li et al., 2026) and microalgae-bacteria consortia based on Chlorella sorokiniana (Nguyen et al., 2026), which extend MBR application to saline and aquaculture effluents where conventional configurations perform poorly.

3.2 Operational aspects

Although MBRs produce high-quality effluent, their operation is influenced by various factors that must be rigorously controlled to ensure performance and longevity. External conditions such as climate, effluent composition, and temperature can impact operation, while controllable parameters include pH, biomass concentration, aeration, TMP, suspended solids (SS), fouling, and critical flux (Belli et al., 2021, Ravadelli et al., 2021).

In aerobic systems, aeration supplies oxygen for microbial degradation of organic matter and maintains biomass in suspension, reducing membrane fouling through shear stress from air bubbles (Belli et al., 2021, Kraume et al., 2009). TMP reflects particle accumulation on the membrane; low and stable TMP favors consistent filtration, particularly in submerged systems operating at lower pressures (Costa et al., 2019, Souza et al., 2020).

High SS concentrations decrease permeate flux due to membrane overloading and increased sludge viscosity. Levels above 40–50 g L^{-1} should be avoided to prevent clogging and performance decline (Belli et al., 2023). Fouling, caused by pore blockage, biofilm formation, inorganic precipitation, and macromolecule adsorption, is a major operational challenge, raising maintenance costs and reducing filtration efficiency (Costa et al., 2018, Guo et al., 2022, Meng et al., 2017).

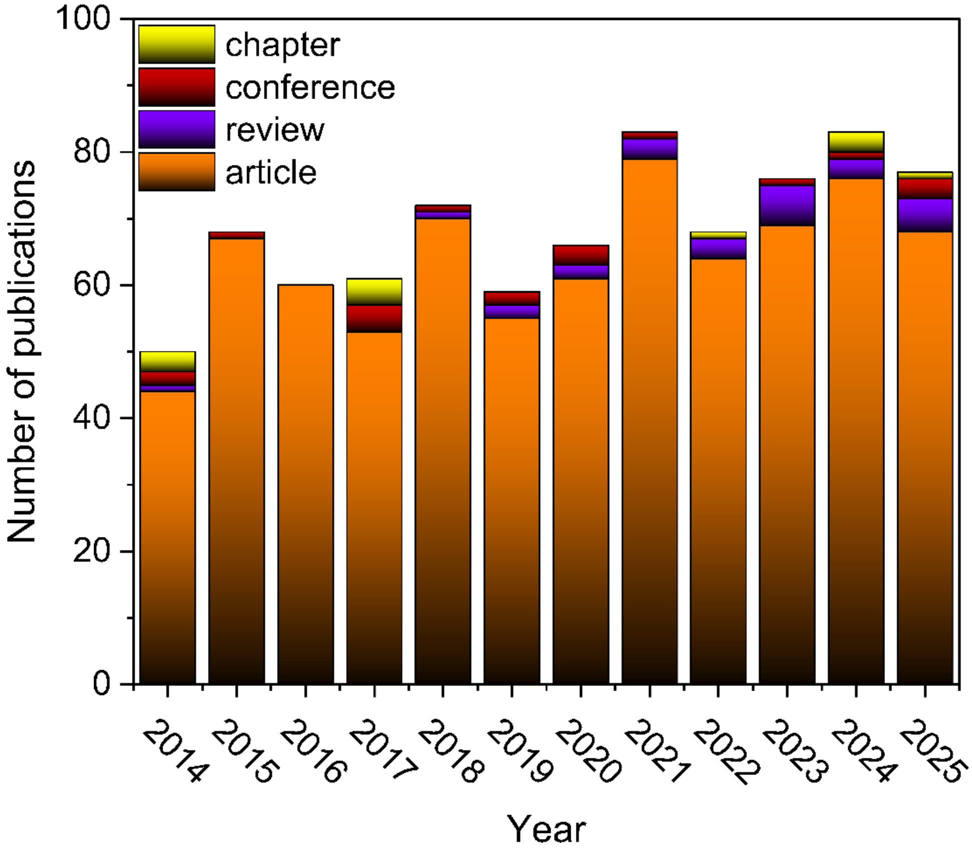
Critical and limiting flux concepts, established in the foundational work of the mid-2000s and retained here for that reason, are key to managing fouling. Critical flux is the highest flux below which fouling is negligible; operating below this threshold minimizes TMP variations (Han et al., 2005, Le-Clech et al., 2006). In contrast, limiting flux is the maximum achievable flux, beyond which increases in TMP do not enhance performance (Bacchin et al., 2006).

4 Systematic review

4.1 Scientometric analysis

Each year, numerous studies examine the operational aspects and configurations of MBRs for wastewater treatment, with a focus on P removal. A bibliometric scan was conducted to map the evolution and thematic structure of the MBR–phosphorus literature and to contextualize the evidence base used in the systematic review. Using the Boolean terms (“MBR” or “membrane bioreactor”) and (“P” or “phosphorus”) and “remov*”, the search retrieved 1266 documents across all years. Restricting the window to 2014–2025, 854 records were identified, comprising 766 articles, 26 reviews, 25 conference papers, and 30 book chapters. The annual output increases (Figure 1), indicating accelerated research activity and technological diversification in MBR-based P removal.

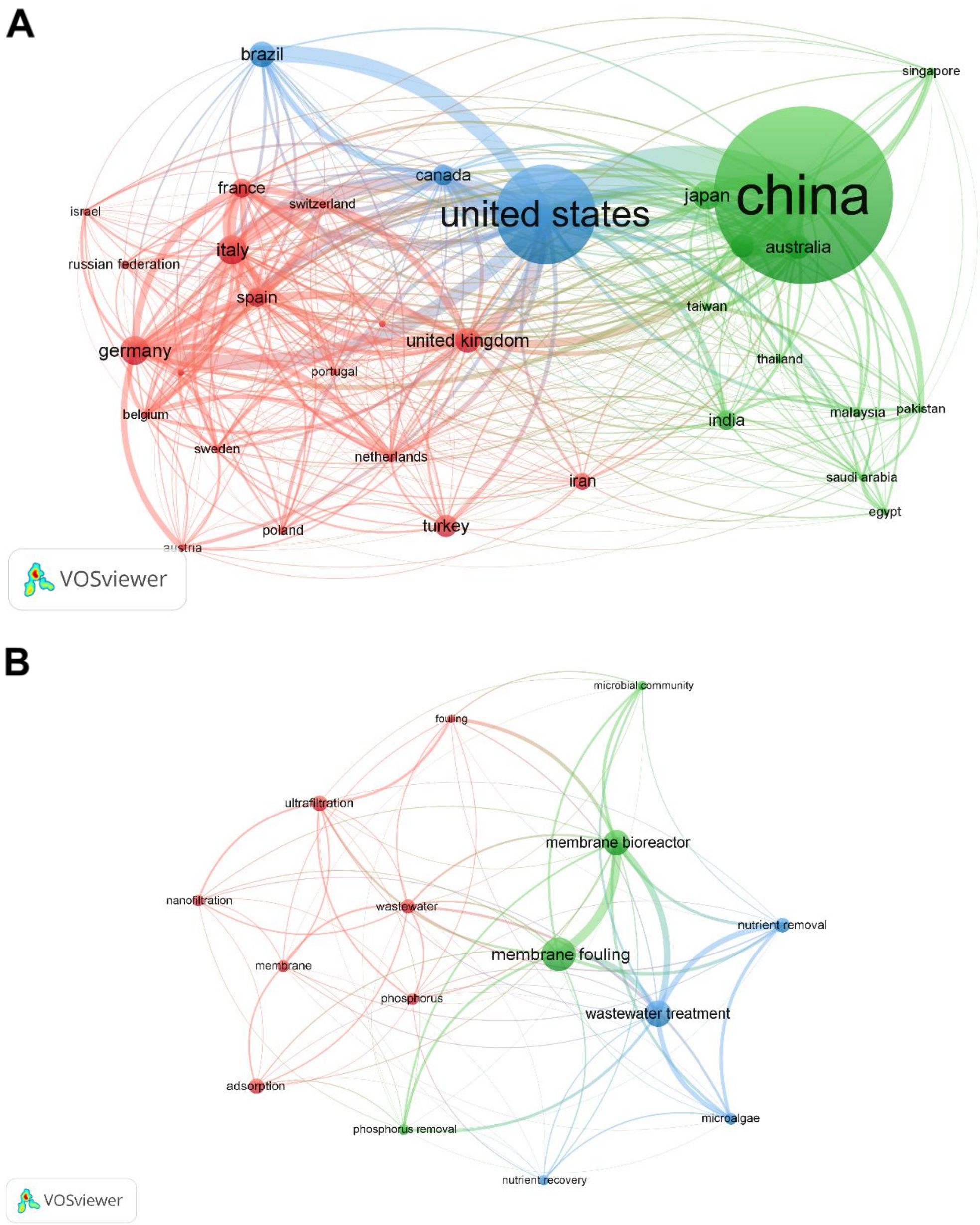
Figure 1: Annual publications and citations on phosphorus removal using membrane bioreactors, 2014–2025. Records retrieved from the Scopus database using the Boolean search string ("membrane bioreactor" OR "MBR") AND ("P" OR "phosphorus") AND "remov*".



Source: Elaborated by author based on Scopus database (2014-2025).

China leads in publications on phosphorus removal using MBRs, contributing 30.1%, followed by the United States with 16.8%. Germany, Japan, and Italy each account for 4.9%, as illustrated in Figure 2A. Other notable contributors include Brazil, the United Kingdom, Australia, and South Korea. China's leading role likely reflects both the severity of its environmental challenges and its investments in water resource recovery technologies and related public policies.

Figure 2: (A) Main contributing countries in the publication of articles on phosphorus removal using membrane bioreactors, and (B) network analysis of the keyword distribution related to the same topic.



Source: Generated using VOSviewer (v1.6.20) from the same set of 854 Scopus records covering the period 2014–2025 described in Figure 1.

Keywords function as standardized terms that encapsulate the core content of research, aiding in topic classification and trend identification. Network analysis of these terms, presented in Figure 2B, reveals correlations among research themes, emerging technologies, and key areas of interest.

"P removal" remains closely linked to MBR technology, reflecting its dual role in nutrient removal and recovery. This suggests a broader focus on parameters such as nitrogen (N), COD, and BOD, indicating a shift from conventional treatment to resource recovery.

Terms like "microbial community" highlight the biological foundation of MBRs, emphasizing the role of microbial consortia in nutrient removal and contaminant degradation. Emerging keywords such as "nanofiltration" and "ultrafiltration" reflect advancements in membrane technologies, while "adsorption" points to integrated or complementary nutrient removal methods.

The recurrence of "fouling" underscores persistent challenges related to membrane clogging, often linked to system configuration and design optimizations aimed at improving operational efficiency.

Overall, the keyword network illustrates the interdisciplinary nature of MBR research, emphasizing its relevance to nutrient recovery, sustainable wastewater treatment, and evolving membrane technologies.

4.2 Influence of parameters

Operational parameters play a crucial role in effluent treatment performance and regulatory compliance. Efficient management improves effluent quality and reduces costs (Diaz et al., 2022).

Key factors such as pH, HRT, SRT, flow rate, TMP, aeration, and PF were consistently evaluated in studies assessing MBR performance for P removal. Several studies also investigated the effects of EC and ET on various effluent types (Chen et al., 2023, Liu et al., 2019, Predolin et al., 2021, Udomkittayachai et al., 2021, Yu et al., 2023).

Various conventional and biologically-driven MBR configurations have been investigated to optimize phosphorus removal, encompassing multi-zone arrangements such as anaerobic/anoxic/aerobic (AAO) systems, hybrid biological configurations, and aerobic-only designs. These configurations exploit distinct microbial communities and zone-specific conditions, particularly anaerobic P release followed by aerobic uptake by phosphorus-accumulating organisms (PAOs), to achieve high removal efficiencies. Table 1 summarizes the key operational parameters and P removal performance reported across these conventional and aerobic MBR configurations.

Table 1: Summary of studies using conventional biological and aerobic MBR configurations for phosphorus removal from wastewater, including key operational parameters and removal efficiency.

MBR configuration	Treatment type	Wastewater type	HRT	TMP	P removal efficiency	Reference
Section A: Multi-zone biological MBR configurations						
Anaerobic Baffled Reactor combined with Membrane Bioreactor (ABR-MBR)	Anaerobic + aerobic	Domestic + Synthetic	7.5 h	NR	RP: 92.0 % $P_{initial}$: 4.19 mg L^{-1} P_{final}: 0.31 mg L^{-1}	Wu et al., 2014
Submerged Hollow Fiber PVDF Membrane Bioreactor (S-MBR)	Aerobic	Domestic	3 h	NR	RP: 80–85 % $P_{initial}$: 11.7–20.3 mg L^{-1}	Ratanatamskul et al., 2015
Anaerobic/Anoxic/Aerobic Membrane Bioreactor with Limited Aeration (AAO-MBR)	Anaerobic Anoxic Aerobic	Municipal	3/3/6.3 h (anaerobic/ anoxic/ aerobic)	30 kPa	RP: 96.7 % $P_{initial}$: 4.72 mg L^{-1} P_{final}: 0.22 mg L^{-1}	Jiang et al., 2021
Anaerobic/Anoxic/Oxic Membrane Bioreactor (AAO-MBR)	Anaerobic Anoxic Aerobic	Municipal	NR	NR	RP: 93 % $P_{initial}$: 2.65–6.15 mg L^{-1} P_{final}: 0.04 mg L^{-1}	Na et al., 2017
Hybrid Membrane Bioreactor (H-MBR) and Conventional Membrane Bioreactor (C-MBR)	Aerobic (hybrid vs. conventional)	Domestic greywater	8 h	NR	RP: 88 % (both) $P_{initial}$: 0.53 mg L^{-1} P_{final}: 0.051 mg L^{-1}	Palmarin & Young, 2019
Anoxic Membrane Bioreactor (An-MBR) [compared with Aerobic MBR — Step I & II]	Anoxic vs. Aerobic	Domestic	Step I / Step II (varying MLSS)	NR	Aerobic MBR Step I: $P_{initial}$: 2.7–5.5 mg L^{-1} P_{final}: 1.3 mg L^{-1}	Khan et al., 2014
Pilot-Scale Membrane Bioreactor (MBR-P) [UCT configuration]	Anaerobic Anoxic Aerobic (UCT)	Municipal	NR	NR	RP: 65.0 % $P_{initial}$: 6.3 mg L^{-1} P_{final}: 3.0 mg L^{-1}	Sayi-Ucar et al., 2015

MBR configuration	Treatment type	Wastewater type	HRT	TMP	P removal efficiency	Reference
Section B: Aerobic MBR configurations						
Aerobic Granular Sludge-Membrane Bioreactor (AGS-MBR)	Aerobic granular sludge	Synthetic	8 h	NR	RP: 30–70 % $P_{initial}$: 28.3 mg L^{-1}	Liu et al., 2022
Dissolved Air Flotation followed by Membrane Bioreactor (DAF-MBR)	Aerobic + pre-treatment DAF	Municipal	NR	5 - 6 bar	RP: 64 % $P_{initial}$: 5.9 mg L^{-1} P_{final}: 2.1 mg L^{-1}	Kim et al., 2015
Aerobic Lateral Flow Granular Sludge Membrane Bioreactor (AGMBR)	Aerobic granular sludge (SBR mode)	Synthetic	170 min cycle	NR	RP: 95 % $P_{initial}$: 34.5 mg L^{-1}	Iorhemen et al., 2018
Membrane Bioreactor with Intermittent Aeration (MBR-IA)	Aerobic Anoxic (intermittent aeration)	Synthetic	Stage I: 8 h Stage II: 8 h	1.0 kPa	Stage I: RP: 66.4 ± 19.2 % Stage III: RP: 54.5 ± 6.2 %	Wang et al., 2015

Notes: HRT = Hydraulic Retention Time; TMP = Transmembrane Pressure; RP = Removal Percentage; $P_{initial}$ = influent P concentration; P_{final} = effluent P concentration; NR = not reported.

Aeration plays a critical role in MBR systems, influencing both biological performance and membrane operation. In AGS-MBR (Aerobic Granular Sludge-MBR) systems, controlled aeration supports nitrification–denitrification processes essential for microbial community development (Liu et al., 2022). In a hybrid DAF-MBR configuration, dissolved air flotation (DAF) pre-treatment reduced organic and solids loading, decreasing membrane fouling potential (Kim et al., 2015).

An intermittently aerated integrated MBR developed for carbon and nitrogen removal and P recovery demonstrated high removal efficiencies while enabling P recovery from sludge (Wang et al., 2015). Intermittent aeration also reduced energy consumption and optimized biological processes.

Further, in an AGMBR operated in sequencing batch reactor (SBR) mode, effective operation was achieved through an aeration cycle of 170 min (Iorhemen et al., 2018). The use of aerobic granular sludge promoted granulation, improved sedimentation, and reduced the sludge volume index, thus lowering membrane fouling risk. Details from these studies are summarized in Table 1, section B.

Efficient P removal heavily depends on the dosage and type of coagulants used, which directly affect membrane fouling (Alibardi et al., 2021, Asif et al., 2021, Lee et al., 2017, Li et al., 2018, Silva et al., 2022, Sun et al., 2019). In the study by Silva et al. (2022), the permeate quality of the MBR was maintained at high standards, with low SS and turbidity concentrations, essential for the MBR's long-term performance. Higher coagulant doses were required when combined with the MBR, despite excellent results compared to other local treatment systems, such as continuous backwash upflow sand filters and high-rate compressible media filters (Alibardi et al., 2021). However, the membrane fouling issue and increased solids concentration raise concerns not only about reduced P removal efficiency but also about higher operational costs.

The effects of different coagulant basicities, specifically PAC (Polyaluminum Chloride), were assessed, revealing that high-basicity PAC minimized negative impacts on microbial activity and preserved biological process efficiency (Lee et al., 2017). An MBR operated with high-basicity PAC showed better stability in terms of TMP and effluent quality, indicating that selecting the correct coagulant basicity can significantly mitigate operational issues.

A similar coagulant-based approach was used with Fe(II) and ozone in the MBR, where iron facilitated P precipitation and ozone broke down extracellular polymeric substances (EPS) and soluble microbial products that contribute to membrane fouling (Asif et al., 2021). $FeCl_3$ and acidogenic co-fermentation were employed to convert iron into a more soluble form, enabling easier P release through pH reduction (Li et al., 2018). Aluminum sulfate was applied in the MBR, slightly enhancing sludge activity and effectively reducing the TMP rise rate from 1.13 KPa d^{-1} to 0.57 KPa d^{-1} (Sun et al., 2019). The data from these studies are summarized in Table 2.

Table 2: Summary of studies using coagulant-assisted MBR configurations for phosphorus removal: coagulant type, class, and removal efficiency

MBR configuration	Coagulant	Coagulant class	Wastewater type	HRT	P removal efficiency	Reference
No coagulant: baseline condition						
Conventional Membrane Bioreactor (C-MBR)	None (baseline)	NR	Domestic	3/6 h	RP: 3.5 % $P_{initial}$: 5.6 mg L^{-1} P_{final}: 5.4 mg L^{-1}	Lee et al., 2017
Aluminum-based coagulants: PAC and aluminum sulfate						
Conventional Membrane Bioreactor (C-MBR)	PAC-B53 (polyaluminum chloride)	Aluminum-based	Domestic	3/6 h	RP: 97.20 % $P_{initial}$: 5.6 mg L^{-1} P_{final}: 0.16 mg L^{-1}	Lee et al., 2017
Conventional Membrane Bioreactor (C-MBR)	PAC-B71 (polyaluminum chloride)	Aluminum-based	Domestic	3/6 h	RP: 97.20 % $P_{initial}$: 5.6 mg L^{-1} P_{final}: 0.16 mg L^{-1}	Lee et al., 2017
Conventional Membrane Bioreactor (C-MBR)	Alumen (aluminum sulfate)	Aluminum-based	Domestic	3/6 h	RP: 94.50 % $P_{initial}$: 5.6 mg L^{-1} P_{final}: 0.31 mg L^{-1}	Lee et al., 2017
Submerged Membrane Bioreactor (S-MBR)	$Al_2(SO_4)_3$ + $FeCl_3$ (combined dosing)	Aluminum + iron (combined)	Domestic	6.8 h	RP: 94.23 % $P_{initial}$: 5.2 mg L^{-1} P_{final}: 0.9 mg L^{-1}	Silva et al., 2022
Iron-based coagulants: $FeCl_3$ and Fe(II)						
Fe(II)-dosed Membrane Bioreactor (Fe-MBR)	Fe(II) (ferrous chloride)	Iron-based	Municipal	11 h	RP: 96 % $P_{initial}$: 10.0 mg L^{-1} P_{final}: 0.4 mg L^{-1}	Asif et al., 2021
Conventional Membrane Bioreactor (C-MBR)	$FeCl_3$ (ferric chloride)	Iron-based	Domestic	NR	RP: 95 ± 3 % $P_{initial}$: 9.18 ± 5.52 mg L^{-1} P_{final}: 0.38 ± 0.21 mg L^{-1}	Alibardi et al., 2021

MBR configuration	Coagulant	Coagulant class	Wastewater type	HRT	P removal efficiency	Reference
Iron + in-situ ozonation						
Fe(II)-dosed + In-situ Ozonation MBR (Fe/O_3-MBR)	Fe(II) + in-situ O_3	Iron + ozonation	Municipal	11 h	RP: 94 % $P_{initial}$: 10.0 mg L^{-1} P_{final}: —	Asif et al., 2021

Notes: HRT = Hydraulic Retention Time; RP = Removal Percentage; $P_{initial}$ = influent P concentration; P_{final} = effluent P concentration; NR = not reported. PAC = Polyaluminum Chloride. Each coagulant condition is presented as a separate row to enable direct comparison.

P removal using MBRs has been investigated under varying hydraulic and solids retention times. In a pilot-scale study, a hollow-fiber submerged MBR operated at an HRT of 7 h and an SRT of 20 d demonstrated effective conditions for microbial metabolic activity related to P removal (Smith et al., 2014). Similarly, the performance of an Integrated Fixed-film Activated Sludge (IFAS-UCT-MBR) system was evaluated under three operational phases with decreasing SRT/HRT ratios—Phase I (56 d / 30 h), Phase II (31 d / 15 h), and Phase III (7 d / 13 h)—revealing high organic matter removal (up to 99%) even at the lowest SRT/HRT configuration (Mannina et al., 2018). This configuration also led to increased organic loading, enhanced nitrogen removal, and higher EPS production, contributing to membrane fouling. Comparative data from both studies are summarized in Table 3.

The influence of HRT on phosphorus performance is not uniform across configurations. A study published after the search window was closed, and therefore cited here for context rather than included in the synthesis, illustrates the point: in internal circulating photogranular MBRs treating synthetic mariculture wastewater, doubling the HRT from 24 to 48 h preserved photogranule structural stability and settleability and extended the fouling cycle, yet produced no meaningful gain in orthophosphate removal, which remained at 34.92 ± 3.94 % and 33.61 ± 7.23 % respectively (Li et al., 2026). This dissociation between hydraulic conditions and phosphorus performance is instructive: where the dominant removal route is assimilation into biomass rather than polyphosphate accumulation, extending contact time improves membrane operation without improving phosphorus uptake. Reported efficiencies of this magnitude also illustrate the point made throughout this review, since they refer explicitly to orthophosphate and are therefore not comparable with the TP values reported by studies in which particulate retention contributes to the reported figure.

Table 3: Synthesis of information regarding operational conditions related to hydraulic and solids retention times (HRT and SRT) in MBR-based systems for phosphorus removal. Operational stages are presented as individual rows to enable direct comparison across studies.

MBR configuration	Wastewater type	Operational stage	HRT	SRT	Permeate flux	P removal efficiency	Reference
Single-phase operation							
Submerged Membrane Bioreactor (S-MBR) MLSS: 12 g L^{-1}	Domestic	Single phase	7 h	20 d	19–26 m^3 d^{-1} CA: 54–170 L min^{-1}	RP: 94.1 % $P_{initial}$: 5.39 mg L^{-1} P_{final}: 0.28 mg L^{-1}	Smith et al., 2014
Multi-stage HRT variation							
Moved Bed Membrane Bioreactor (MB-MBR) TSS: 3.0 g L^{-1}	Domestic	**Stage I**	30 h	NR	21 L m^{-2} h^{-1}	RP: 87.5 % $P_{initial}$: 7.82 mg L^{-1} P_{final}: 0.92 mg L^{-1}	Mannina et al., 2018
		Stage II	15 h	NR	26 L m^{-2} h^{-1}	RP: 90.5 % $P_{initial}$: 13.72 mg L^{-1} P_{final}: 1.30 mg L^{-1}	
		Stage III	13 h	NR	29 L m^{-2} h^{-1}	RP: 96.6 % $P_{initial}$: 12.24 mg L^{-1} P_{final}: 0.42 mg L^{-1}	
Configuration comparison at fixed HRT/SRT							
Anoxic/Oxic MBR (A/O-MBR) vs. C-MBR and MB-MBR	Synthetic	Single phase	8 h	30 d	NR	A/O-MBR: RP: 69.7 % C-MBR and MB-MBR: lower efficiency reported	Khan et al., 2014
Multi-stage operation with Fe(II) co-fermentation							
MBR with Fe(II) dosing and Acidogenic Co-fermentation (MBR/Fe/Ac)	Municipal	**Stage I (days 1–60)**	12 h	NR	17.4 L m^{-2} h^{-1}	RP: 70.6 % $P_{initial}$: 6.35 mg L^{-1}	Li et al., 2018
		Stage II	12 h	NR	17.4 L m^{-2} h^{-1}	RP: 87.7 %	

MBR configuration	Wastewater type	Operational stage	HRT	SRT	Permeate flux	P removal efficiency	Reference
MLSS: 4.0–5.5 g L^{-1}		**(days 61–120)**				$P_{initial}$: 5.04 mg L^{-1}	
		Stage III (days 121–190)	12 h	NR	17.4 L m^{-2} h^{-1}	RP: 96.4 % $P_{initial}$: 5.34 mg L^{-1}	
Study group E — Coagulant dosage stages at fixed HRT							
Submerged MBR with $Al_2(SO_4)_3$ dosing (S-MBR)	Municipal	**Stage I (0 mg L^{-1} dose)**	18 h	NR	16 L m^{-2} h^{-1}	RP: 84.4 % $P_{initial}$: 4.72–5.22 mg L^{-1} P_{final}: 0.72 mg L^{-1}	Sun et al., 2019
		Stage II (10 mg L^{-1} dose)				RP: 92.0 % $P_{initial}$: 4.63–5.02 mg L^{-1} P_{final}: 0.40 mg L^{-1}	
		Stage III (0 mg L^{-1} dose)				RP: 71.1 % $P_{initial}$: 4.88–5.16 mg L^{-1} P_{final}: 1.45 mg L^{-1}	
		Stage IV (50 mg L^{-1} dose)				RP: 90.6 % $P_{initial}$: 4.89–5.05 mg L^{-1} P_{final}: 0.47 mg L^{-1}	

Notes: HRT = Hydraulic Retention Time; SRT = Solids Retention Time; RP = Removal Percentage; $P_{initial}$ = influent P concentration; P_{final} = effluent P concentration; MLSS = Mixed Liquor Suspended Solids; CA = Continuous Aeration; NR = not reported. Operational stages of the same study are presented as individual rows to enable direct comparison across phases.

Various MBR configurations have been investigated to optimize P and nitrogen removal in synthetic wastewater treatment. In one study, three systems—conventional MBR (C-MBR), moving-bed MBR (MB-MBR), and anoxic/oxic MBR (A/O-MBR)—were compared for nutrient removal performance (Khan et al., 2014). The A/O-MBR, which integrates anoxic and oxic zones within a single reactor, enabled simultaneous nitrification and denitrification, thereby enhancing nitrogen and P removal through the activity of phosphorus-accumulating organisms (PAOs). Operating conditions of 8 h HRT and 30 d SRT supported microbial development for effective nutrient removal. This configuration also showed reduced membrane fouling and extended filtration cycles due to lower concentrations of soluble and bound EPS. Additionally, the use of Kaldnes® media in both MB-MBR and A/O-MBR systems decreased the sludge load on the membrane, improving filtration performance.

A comparison between C-MBR and a hybrid MBR with biocarriers operating under 8 h HRT and 40 d SRT also demonstrated effective nutrient removal, highlighting the benefits of integrated biofilm systems (Palmarin and Young, 2019). Similarly, a system composed of an anaerobic stage followed by alternating anoxic and oxic phases (An-M(A/O)-MBR) emphasized the importance of reactor configuration and influent management to maintain a balance of aerobic and anoxic microbial communities (Yuan et al., 2015).

Phase alternation under variable temperature conditions was also tested to evaluate P removal efficiency. Results showed that factors such as influent P concentration, organic substrate availability, and HRT directly influenced the activity of PAOs (Sayi-Ucar et al., 2015). A combined system using a compartmentalized anaerobic baffled reactor (ABR) followed by an MBR operated at 7.5 h HRT and 200% recirculation ratio provided favorable conditions for nutrient removal (Wu et al., 2014). A similar configuration with a shorter HRT of 3 h—2 h in the ABR and 1 h in the aerobic MBR—led to intensified PAO activity and high P removal (Ratanatamskul et al., 2015).

The effect of aeration on nutrient removal was assessed using an anaerobic/anoxic/aerobic MBR (AAO-MBR), where flows of 25–40 L m^{-2} h^{-1} were applied (Jiang et al., 2021). Limited aeration enhanced anaerobic P release, supported simultaneous nitrification and denitrification, and improved hydrolysis of particulate organic matter, resulting in high P removal efficiency.

In contrast, a four-stage MBR system with anaerobic, anoxic, and aerobic phases and 7.5 h HRT showed higher effluent P concentrations (0.9 mg L^{-1}) and 20% lower membrane permeability, suggesting challenges in settling and membrane performance in the anoxic phase

(H. Lee et al., 2015). Finally, a pilot-scale MBR using metabolic uncoupling through an anaerobic sludge retention tank successfully reduced sludge production and increased P accumulation by extending SRT and analyzing different polyphosphate fractions (Na et al., 2017). The data from these electrocoagulation-assisted studies, including electric field parameters and removal efficiencies, are summarized in Table 4.

Table 4: Summary of studies using electrocoagulation-assisted MBR configurations for phosphorus removal: electrocoagulation mechanism, electrode material, current density, and removal efficiency.

MBR configuration	EC mechanism	Electrode material	Current density/ Applied potential	Wastewater type	HRT	Fouling rate	P removal efficiency	Reference
Electric field-controlled dynamic MBR								
Electric Field-Controlled Dynamic MBR (E-DMBR-Ti) MLSS: —	Electric field	Titanium anode	**4.5 V**	Synthetic	11 h	2.28 kPa h^{-1}	P removal not reported for the Ti anode; the aluminium anode was introduced by the authors to overcome the low P removal of this configuration	Chen et al., 2023
Electric Field-Controlled Dynamic MBR (E-DMBR-Al) MLSS: —	Electrocoagulation	Aluminum anode	**2.4 A m^{-1}**			5.15 kPa h^{-1} at 2.4 A m^{-1}: 8.41 at 0.8 A m^{-2}; 9.14 at 4.8 A m^{-2}	RP: 94.69 % (median, at 2.4 A m^{-2}) $P_{initial}$: ≈ 3.5 mg L^{-1}	
Submerged Membrane Electro-Bioreactor: current density gradient								
Submerged Membrane Electro-Bioreactor (SMEBR) MLSS: 3.3–10.6 g L^{-1} EPS: 78–152 mg g^{-1}	Electrocoagulation	Al anode stainless steel cathode	**0 A m^{-2} (baseline)**	Domestic + industrial	16 h	0.81 kPa d^{-1}	RP: 61.4 % $P_{initial}$: 15.8 mg L^{-1} P_{final}: 6.1 mg L^{-1}	Predolin et al., 2021
			5 A m^{-2}				RP: 92.4 % $P_{initial}$: 8.3 mg L^{-1} P_{final}: 0.67 mg L^{-1}	
			10 A m^{-2}				RP: 97.7 % $P_{initial}$: 11.0 mg L^{-1} P_{final}: 0.33 mg L^{-1}	
			15 A m^{-2}				RP: 97.9 % $P_{initial}$: 15.0 mg L^{-1} P_{final}: 0.29 mg L^{-1}	
Electro Membrane Bioreactor vs. C-MBR								

Electro Membrane Bioreactor (E-MBR) MLSS: 8.31 g L^{-1} EPS: 23.70 mg g^{-1}	Electrocoagulation	Iron anode-cathode membrane	0.4 V	Synthetic	10 h	NR	RP: 89.1 % $P_{initial}$: 7.3 mg L^{-1} P_{final}: 0.8 mg L^{-1}	Yu et al., 2023
Electroconductive Moving Bed MBR — current density comparison								
Electroconductive Moving Bed MBR (EcMB-MBR) MLSS: 8 g L^{-1} MLVSS: 6 g L^{-1}	Electrocoagulation (intermittent EC)	Conductive floating media (electrodes)	**10 A m^{-2}**	Domestic	4 h	NR	RP: 99.5 % $P_{initial}$: 4.56 mg L^{-1}	Udomkittayachai et al., 2021
			15 A m^{-2}				RP: 99.5 % (comparable)	
			20 A m^{-2}				RP: 99.5 % (comparable)	
Aerobic Granular Sludge MBR with electrocoagulation								
Aerobic Granular Sludge MBR (AGS-MBR)	Electrocoagulation (electrostatic repulsion)	Iron anode-cathode membrane	NR	Synthetic	8 h	NR	RP: 30–70 % $P_{initial}$: 28.3 mg L^{-1} 180-day operation P recovery potential	Liu et al., 2022

Notes: EC = Electrocoagulation; TMP = Transmembrane Pressure; HRT = Hydraulic Retention Time; RP = Removal Percentage; $P_{initial}$ = influent P concentration; P_{final} = effluent P concentration; EPS = Extracellular Polymeric Substances; PAO = Phosphorus-Accumulating Organisms; MLSS = Mixed Liquor Suspended Solids; MLVSS = Mixed Liquor Volatile Suspended Solids; NR = not reported. Each current density condition is presented as a separate row; row shading groups rows belonging to the same study.

An innovative configuration combining a membrane bioreactor with an oxidation ditch design and inclined tubes (IT/OD-MBR) was evaluated with a focus on horizontal flow velocity as a parameter influencing nutrient removal (Ratanatamskul and Romskul, 2022). Flow velocities ranging from 0.2 to 0.4 m s^{-1} were tested, and although only minor variations in permeate flux efficiency were observed, higher velocities contributed to a reduction in TSS and yielded promising results for overall performance.

In Brazil, the first full-scale MBR with biological tertiary treatment capability was implemented at the EPAR Capivari II wastewater treatment plant, operated by SANASA in Campinas/SP, and reported as the first full-scale municipal MBR in Latin America. The plant was commissioned in April 2012 with an average design flow of 182 L s^{-1} and approximately 36,400 m^2 of installed membrane area, and achieved 73.0 % total phosphorus removal, reducing influent concentrations of 8.2–10.0 mg L^{-1} to a permeate average of 3.05 mg L^{-1} (Pagotto et al., 2014). However, P removal efficiency was shown to be sensitive to the complexity of biological processes within the MBR. To address this, adjustments in operational parameters and system design have been proposed. One such strategy is the introduction of a secondary sludge recirculation loop, redirecting sludge from the end of the aerobic zone to the beginning of the anoxic zone. This modification could lower residual nitrate concentrations reaching the anaerobic zone, thereby enhancing conditions for PAOs and improving P removal efficiency. The data from these studies are summarized in Table 5.

Full-scale operating data remain scarce relative to the bench- and pilot-scale literature, although they are not absent: outside the search window, nutrient removal has been characterized at full-scale MBR sewage treatment plants elsewhere, including through data-driven modelling of long operating series (Yaqub and Lee, 2022), and pilot-scale work has begun to report energy performance alongside removal efficiency (Kim et al., 2026). What is lacking for the Brazilian context specifically is documentation rather than installations: additional full-scale MBRs are understood to be in operation, but peer-reviewed characterization of their nutrient performance has not been published, which leaves EPAR Capivari II as the only Brazilian full-scale case for which operating data can be cited. This is itself a gap worth addressing, since design decisions in the sector are currently informed by evidence generated almost entirely at reduced scale and under other climatic and influent conditions.

Table 5: Summary of information regarding operational conditions related to new provisions for MBRs

MBR configuration	Wastewater type	Aeration rate	Aeration mode	TMP	Permeate flux	SRT	P removal efficiency	Reference
Submerged Membrane Bioreactor (S-MBR) MLSS: 12 g L^{-1} HRT: 7 h	Domestic	54–170 L min^{-1}	Continuous	≤0.01 NTU	19–26 m^3 d^{-1}	20 d	RP: 94.1 % $P_{initial}$: 5.39 mg L^{-1} P_{final}: 0.28 mg L^{-1}	Smith et al., 2014
Anaerobic/Anoxic/Aerobic MBR (AAO-MBR) HRT: 3/3/6.3 h	Municipal	NR	Limited aeration	30 kPa	25–40 L m^{-2} h^{-1}	NR	RP: 96.7 % $P_{initial}$: 4.72 mg L^{-1} P_{final}: 0.22 mg L^{-1}	Jiang et al., 2021
Anaerobic/Anoxic/Oxic MBR (AAO-MBR) MLSS: 8–10 g L^{-1} SRT: 198.7 d	Municipal	40–50 L m^{-2} h^{-1}	Continuous	NR	83 m^3 d^{-1}	198.7 d	RP: 93 % $P_{initial}$: 2.65–6.15 mg L^{-1} P_{final}: 0.04 mg L^{-1}	Na et al., 2017
Multi-Anoxic/Oxic Anaerobic MBR (An-M(A/O)-MBR) MLSS: —	Municipal	NR	Step-feed	NR	NR	NR	RP: ~90 % (operational flexibility noted)	Yuan et al., 2015
MBR with ZeeWeed® 500D Ultrafiltration Design ADF: 182 L s^{-1} (≈ 15,700 m^3 d^{-1}) Membrane area: ≈ 36,400 m^2	Municipal	NR	Suction-driven hollow fiber	NR	15-18 LMH (average 17)	NR	RP: 73.0 % $P_{initial}$: 8.2–10.0 mg L^{-1} (mean 9.1) P_{final}: 0.98–7.35 mg L^{-1} (mean 3.05)	Pagotto et al., 2014
Membrane Bioreactor with Intermittent Aeration (MBR-IA) MLSS: 7.85 g L^{-1} HRT: 8 h (both stages)	Synthetic	IA: 25/20 min ON/OFF	Intermittent	1.0 kPa	20–27 L m^2 h^{-1}	NR	Stage I: RP: 66.4 ± 19.2 % Stage II: RP: 45.1 ± 11.5 % Stage III: RP: 54.5 ± 6.2 %	Wang et al., 2015

Notes: HRT = Hydraulic Retention Time; SRT = Solids Retention Time; TMP = Transmembrane Pressure; RP = Removal Percentage; $P_{initial}$ = influent P concentration; P_{final} = effluent P concentration; MLSS = Mixed Liquor Suspended Solids; NR = not reported. Aeration rate and mode are reported as provided in each original study; units vary across studies.

4.3 Mechanisms of phosphorus removal in MBR systems

Reported removal efficiencies are only interpretable when the underlying mechanism is identified, because different mechanisms act on different P fractions and respond differently to operational change. Five mechanisms operate in MBR-based systems, frequently in combination.

Biological uptake by PAOs is the principal route in configurations that provide an anaerobic zone upstream of an aerobic zone. Under anaerobic conditions, PAOs hydrolyse intracellular polyphosphate and release orthophosphate to the bulk liquid, using the energy released to take up VFAs and store them as polyhydroxyalkanoates (PHAs). On transfer to the aerobic zone, the stored PHAs are oxidized and the energy recovered is used to take up orthophosphate in excess of growth requirements, restoring the polyphosphate reserve. Net removal therefore occurs only when P-enriched biomass is withdrawn from the system, which makes sludge wastage an integral part of the mechanism rather than an operational side effect. The organisms responsible are functionally heterogeneous: alongside Candidatus Accumulibacter, Tetrasphaera-related organisms contribute through distinct metabolic routes (Wang et al., 2023), and not all PAOs possess denitrifying P-uptake capability (Zhao et al., 2024), which constrains the extent to which anoxic zones can substitute for aerobic uptake. Polyphosphate stored extracellularly has also been shown to participate alongside the intracellular pool (Long et al., 2021).

Chemical precipitation removes dissolved orthophosphate by forming sparingly soluble solids. Dosing of aluminium or iron salts yields amorphous metal phosphates and hydroxo-phosphate complexes, whose formation is strongly pH-dependent; in the presence of magnesium and ammonium, struvite may form, and at elevated calcium concentrations hydroxyapatite becomes the thermodynamically favored phase (Nadagouda et al., 2024). Because the products are retained as solids, the membrane converts what would otherwise be a clarification problem into complete retention — which is precisely why coagulant-assisted MBRs achieve very low effluent P concentrations.

Co-precipitation and adsorption onto the floc constitute a third route, in which orthophosphate associates with metal hydroxide surfaces and with extracellular polymeric substances (EPS) already present in the mixed liquor. This route is difficult to quantify separately from precipitation, and the two are commonly reported together.

Electrocoagulation generates the coagulant in situ through anodic dissolution of a sacrificial aluminium or iron electrode, producing metal cations that hydrolyze to reactive hydroxides and bind phosphate without the addition of counter-ions such as chloride or sulphate (Reza et al., 2024). Applied current density controls the dosing rate, and an optimum exists: the study of Chen et al. (2023) reported the highest P removal and the lowest fouling rate at 2.4 A m^{-2}, with performance declining at both 0.8 and 4.8 A m^{-2}. The simultaneous electrophoretic effect on sludge particles also alters floc size, which is why electro-assisted systems frequently report fouling mitigation and P removal as coupled outcomes (Hu et al., 2024).

Physical retention by the membrane, finally, removes particulate and colloidal P irrespective of the biological or chemical route, and is the mechanism most often conflated with the others. Since TP includes particulate P, a system may report high TP removal while achieving little removal of dissolved orthophosphate. This distinction is the principal reason why the studies synthesized here are discussed with explicit reference to the P fraction measured.

4.4 Role of volatile fatty acids

The availability of VFAs is the single most influential factor governing biological P removal in MBR systems, because the anaerobic uptake of VFAs is the energetic step that drives subsequent aerobic P uptake. Where readily fermentable substrate is scarce, PAOs cannot accumulate sufficient PHA, the aerobic uptake phase is correspondingly limited, and removal efficiency falls. This mechanism accounts for several observations in the studies reviewed: the decline in efficiency reported by Yuan et al. (2015) was attributed to insufficient organic carbon for P release in the anaerobic tank, and the maximum efficiency observed by Mannina et al. (2018) coincided with the phase presenting the highest acetate concentration.

The composition of the VFA pool matters as well as its magnitude. Acetate and propionate are the dominant species generated during sludge fermentation, and they are not metabolically equivalent: differences in carbon-uptake bioenergetics between PAOs and glycogen-accumulating organisms (GAOs) determine which population prevails under a given substrate regime, with PAOs holding a competitive advantage where VFAs are limiting and a broader range of organisms competing for substrate where VFAs are abundant (Chen et al., 2022). Because GAOs consume VFAs without contributing to P removal, conditions favoring GAO proliferation reduce efficiency without any change in reactor configuration.

Where influent VFA content is insufficient, in situ generation offers an alternative to external carbon dosing. Side-stream acidogenic fermentation of waste sludge produces VFAs internally, and when combined with iron dosing it simultaneously supports biological uptake and creates the acidic conditions required to release P from the resulting iron-phosphate solids (Li et al., 2018, Li et al., 2019). This coupling is significant because it converts sludge from a disposal burden into a carbon source, and because it addresses the recovery constraint discussed below.

Carbon availability can also be managed by distribution rather than by dosing. In a pilot-scale MBR reported after the close of the search window, automatic splitting of the influent organic carbon between reactor zones in response to the measured C/N ratio maximized denitrification without any external carbon addition, while a hybrid jet venturi mixer supplied aeration and mixing at reduced energy demand; the system achieved 91.2 % total phosphorus removal alongside 78.2 % total nitrogen removal (Kim et al., 2026). The relevance to phosphorus is that internal carbon is a shared resource: carbon directed to denitrification is carbon unavailable for anaerobic VFA uptake by PAOs, so the allocation of influent organic matter between zones is itself an operational parameter governing phosphorus performance.

4.5 P removal efficiency

The combination of MBRs and electrocoagulation resulted in phosphorus removal efficiencies of 94.7 %, 97.9 %, up to 70 %, 89.1 %, 99.5 %, 92.4 %, and 98.5 % (Battistelli et al., 2018, Chen et al., 2023, Liu et al., 2019, Predolin et al., 2021, Udomkittayachai et al., 2021, Yu et al., 2023). Yu et al. (2023) further emphasized that the absence of electrocoagulation reduced efficiency to 52.70 %, indicating the lower effectiveness of C-MBR in their study.

Phosphorus removal efficiency varied across the intercellular and intracellular stages of the AGS system (Liu et al., 2022). Initially, P accumulated in the AGS intercellular phase, achieving substantial effluent removal. However, the lack of regular sludge removal in the AGS-MBR system led to the conversion of accumulated solid P into water-soluble, bioavailable P, resulting in efficiency fluctuations between 30 % and 70 %, with AGS-MBR as the primary treatment. Aerobic granular sludge achieved efficiencies above 95 % due to its stratified structure, promoting aerobic conditions on the surface and anaerobic conditions in the core, combined with the aerobic granular sludge reactor as primary treatment (Iorhemen et al., 2018). This configuration was essential for effective P removal, allowing PAOs to store nutrients during the anaerobic phase and release them during the aerobic phase. The results of Iorhemen et al. (2018) were superior to those of Liu et al. (2022), an outcome attributed to greater operational control and smaller scale.

The DAF-MBR system achieved 64 % P removal efficiency (Kim et al., 2015), even without coagulants, often used to precipitate P, showing that MBR preceded by dissolved air flotation can enhance nutrient removal.

Over 90 % P removal efficiency was achieved with coagulants added to the MBR permeate (Alibardi et al., 2021, Silva et al., 2022). Due to low turbidity, SS, and colloidal and soluble components, chemical usage was much lower (Von Sperling, 2015). High-basicity PAC (71 %) was more effective for P removal (97 %) while maintaining MBR stability and minimizing adverse effects on microbial activity (Lee et al., 2017). Lower-basicity coagulants negatively impacted organic matter degradation due to increased chloride ions (Lee et al., 2017).

Using Fe(II) and ozone, Asif et al. (2021) obtained efficiencies above 95 %, reducing P concentrations from approximately 10 mg L^{-1} in raw effluent to about 0.03 mg L^{-1} in treated effluent. Li et al. (2018) achieved 95.6 % removal with 20 mg L-1 $FeCl_3$, similar to Asif et al. (2021). Aluminum sulfate at 10 mg L^{-1} reached 92 % efficiency (Sun et al., 2019), also reducing membrane fouling by increasing sludge particle size and decreasing EPS.

MBR operation not only maintained P removal efficiency but improved the process over conventional treatment (Smith et al., 2014). Effluent P concentrations were reduced to 0.28 ± 0.32 mg L-1, with 94.1 ± 8.3 % removal efficiency.

Variable HRT and SRT phases showed efficiency between 87.5 % and 96.6 %, with the maximum in phase III (13 h / 7 d), possibly due to higher COD concentrations, particularly high acetate levels in the effluent (Mannina et al., 2018).

IT/OD-MBR technology achieved over 90 % P removal, reducing permeate concentrations to 0.37, 0.46, and 0.44 mg L-1 for horizontal flow velocities of 0.2, 0.3, and 0.4 m s-1, respectively (Ratanatamskul and Romskul, 2022), indicating high P removal capability under different flow conditions.

A/O-MBR demonstrated superior P removal compared to other MBR configurations due to its unique setup and biomass management (Khan et al., 2014). Integrating anoxic and oxic zones improved nutrient removal efficiency, achieving 69.7 ± 7.7 % P efficiency and prolonging operational cycles.

Hybrid MBR achieved P removal efficiencies equal to or higher than C-MBR, with an average of 90 % for both, attributed to biofilms within the HMBR enhancing simultaneous nitrification and denitrification (Palmarin and Young, 2019). Yuan et al. (2015) achieved 84.5 % efficiency, with effluent P concentrations below 1.0 mg L-1. However, efficiency declined due to a lack of organic carbon necessary for P release in the anaerobic tank. Wang et al. (2015) reported an average efficiency of 53.3 % (± 29.7 %). Lower influent P concentration (6.7 mg L-1) resulted in 66.4 % removal, while an increase to 12 mg L-1 dropped efficiency to 45.1 %, suggesting saturation in P absorption capacity.

Temperature variations directly related to P removal efficiency (Sayi-Ucar et al., 2015), with the highest efficiency (95 %) at 24 °C and 50 % above 35 °C. Integrating the anaerobic sludge retention tank with the MBR achieved a high P removal efficiency of 93 %, demonstrating that metabolic decoupling promoted increased P synthesis, accumulated as insoluble acid polyphosphate usable under growth-limiting conditions (Na et al., 2017).

P removal was achieved through anaerobic P release in ABR followed by aerobic assimilation in MBR (Wu et al., 2014). The combination maximized PAO activity, with an average total P removal efficiency of 92 %. Ratanatamskul et al. (2015) achieved slightly lower efficiency (80 - 85 %) with the same configuration. Jiang et al. (2021) demonstrated 96.7 % efficiency at a flow rate of 30 L m-2 h-1, identified as optimal and reducing membrane fouling.

As reported by Lee et al. (2015), effluent P concentrations were higher in anoxic MBR than aerobic MBR, indicating lower nutrient removal efficacy in the anoxic process, likely due to different P uptake dynamics of PAOs. Implementing MBR with different phases requires precise operational adjustments for better P removal.

A Brazilian study indicated that ideal conditions for continuous, efficient PAO operation were not fully achieved, with an average efficiency of 73 % and effluent P concentrations ranging from 0.98 mg L-1 to 7.35 mg L-1 (Pagotto et al., 2014). Coagulant dosing is planned in Phase II to achieve even lower effluent P concentrations, ensuring effective removal regardless of biological process variations.

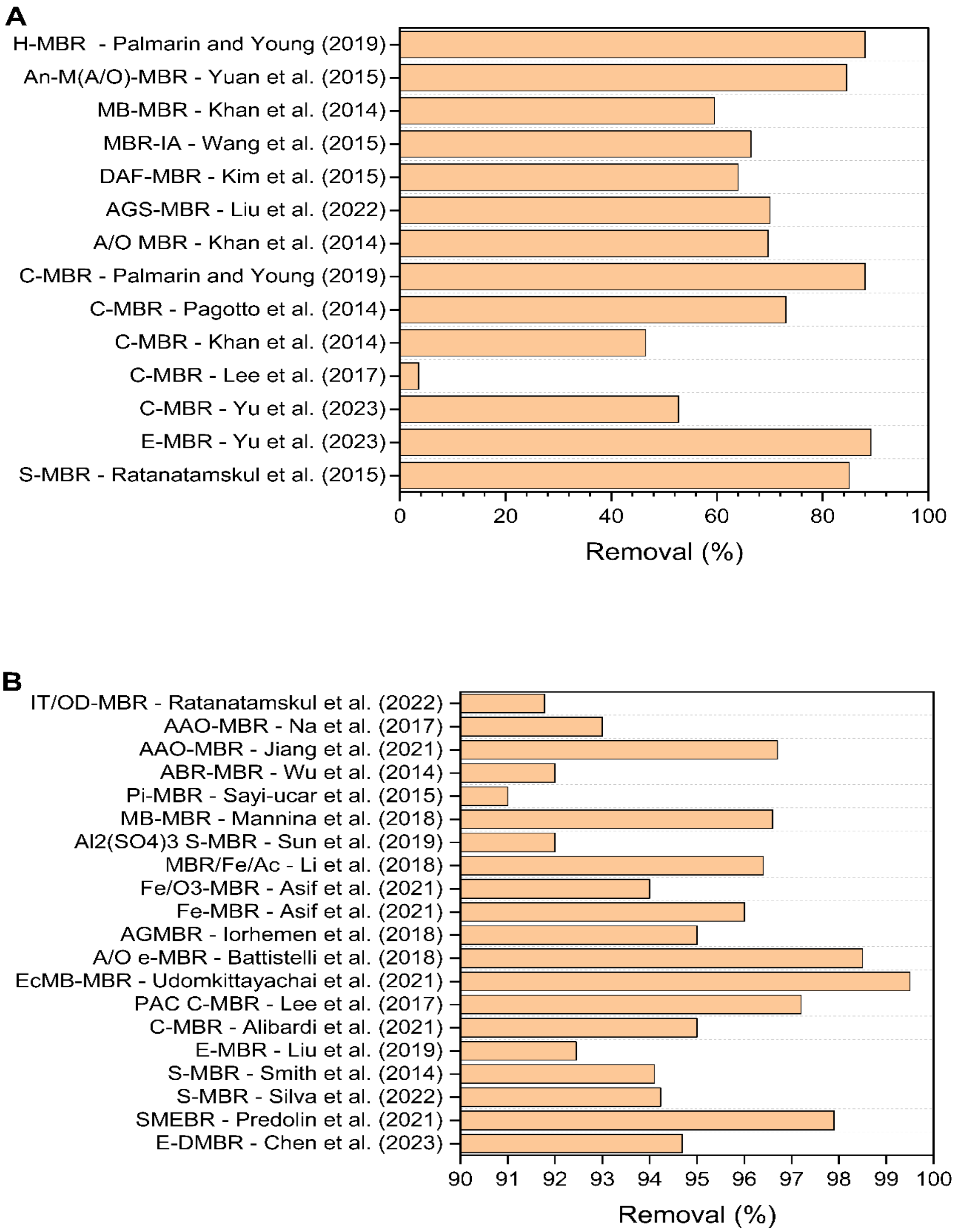
Figure 3 synthesizes and relates the findings, comparing various membrane bioreactor technologies and their P removal efficiencies. Choosing an MBR technology should consider the necessary P removal efficiency, operating and maintenance costs, and system complexity. High-efficiency technologies may be preferred in areas with stricter environmental regulations, while moderate-efficiency options may be suitable for preliminary or less restrictive treatments. Segregating studies with maximum efficiencies above 90 % and below this threshold created two separate charts (Figures 3A and 3B).

Overall, all reviewed studies yielded positive results in P removal. However, most approached 90 %, highlighting the high efficiency of membrane bioreactors. Configurations involving electrocoagulation, coagulant addition, and/or integration with other treatment systems stood out as primary or polishing steps.

Evidence published after the search window, cited here for context and not included in the synthesis, qualifies this trade-off rather than confirming it as inevitable. Where fouling is addressed through sludge morphology and microbial regulation instead of through hydraulic or chemical means, low effluent phosphorus and stable transmembrane pressure have been reported simultaneously and under demanding conditions (Wu et al., 2026). This suggests that the coupling observed across much of the literature reviewed here reflects the particular strategies adopted (coagulant dosing and elevated biomass concentrations) rather than a necessary relationship between phosphorus removal and membrane fouling.

The keyword nutrient recovery warrants explicit treatment, because removing P from the liquid phase and recovering it as a usable product are distinct achievements, and the studies synthesized here overwhelmingly demonstrate the former. Phosphorus removed in an MBR accumulates either in the biomass as intracellular polyphosphate or in chemical precipitates within the sludge, and neither form is directly usable as fertilizer. Phosphorus bound to aluminium or iron is of low plant availability, and its release requires acidification or anaerobic conditions before any crystallization step can proceed; this is the constraint that acidogenic co-fermentation with iron dosing is designed to overcome, converting the bound P into a soluble form recoverable from the sludge liquor (Li et al., 2019). Struvite crystallization is the most mature recovery route, but it requires a P-rich, low-solids liquor, adequate magnesium, and pH control, and its yield and product quality are sensitive to competing ions, calcium in particular (Cañas et al., 2023). Alternative routes applied specifically to membrane systems include adsorption from AnMBR permeate (Hafuka and Kimura, 2022) and precipitation with magnesium-based pellets integrated into an AAO-MBR (Eghombi et al., 2022). Beyond process constraints, the agricultural use of sludge-derived P is limited by co-accumulated contaminants and by regulatory frameworks that differ substantially between jurisdictions. Recovery from MBR systems is therefore best understood as a downstream operation enabled by, but not equivalent to, the removal performance reported in this review.

Figure 3: Different MBR configurations applied in P removal with efficiencies (A) below 90% and (B) above 90%



Source: Values correspond to the maximum removal reported by each study for the P fraction stated in Tables 1 to 5. Abbreviations used in the chart are defined in the list of abbreviations at the end of this document.

Table 6 presents data from selected articles, showcasing the processes and advantages of each MBR technology for P removal in effluents. This provides a comparative analysis, highlighting the robustness and effectiveness of MBRs in meeting stringent treatment and reuse requirements.

By presenting various configurations and their efficiencies, Table 6 underscores the importance of selecting the most suitable technology based on proven performance. It also serves as a reference for future research in the sanitary field, indicating applications needing further testing and those already well-established.

Authors integrating electrocoagulation with MBR reaffirmed its greater efficacy in P removal and membrane fouling control (Chen et al., 2023, Liu et al., 2019, Predolin et al., 2021, Udomkittayachai et al., 2021, Yu et al., 2023).

Conversely, the application of coagulants as a complement to MBR treatment effectively supplemented the process while providing greater operational stability (Alibardi et al., 2021, Asif et al., 2021, Lee et al., 2017, Li et al., 2018, Silva et al., 2022, Sun et al., 2019).

Meanwhile, MBRs associated with other technologies and/or featuring zone variations optimize space usage through process integration, enhancing treatment outcomes without chemical additions (Jiang et al., 2021, Khan et al., 2014, H. Lee et al., 2015, Na et al., 2017, Palmarin and Young, 2019, Ratanatamskul et al., 2015, Sayi-Ucar et al., 2015, Wu et al., 2014, Yuan et al., 2015).

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Table 6 Summary of applied processes and main advantages related to studies using MBRs for P removal.

MBR configuration	Applied process	Main advantages	Ref
Electric Field-Controlled Dynamic Membrane Bioreactor (E-DMBR)	E-DMBR-Ti: with titanium anode E-DMBR-Al: with aluminum anode and electrocoagulation technology	E-DMBR-Ti: The application of an electric field significantly reduced the membrane fouling rate (↓ 48.99 %) E-DMBR-Al: Electrocoagulation increased the abundance of electroactive microorganisms and PAOs, contributing to excellent P removal (94.69 %)	(Chen et al., 2023)
Submerged Membrane Bioreactor with Electrocoagulation (S-MEBR)	Submerged with aluminum anode and stainless steel cathode	Significant fouling reduction (TMP - 72.80 % and EPS - 55.50 %) Improved effluent quality with a 34.60 % increase in P removal	(Predolin et al., 2021)
Aerobic Granular Sludge Membrane Bioreactor (AGS-MBR)	Electrocoagulation with an anode-cathode iron membrane and electrostatic repulsion	180-day operation without sludge disposal Identification of distribution of different P fractions Potential for P recovery	(Liu et al., 2022)
Electrochemical Membrane Bioreactor (E-MBR)	Electrocoagulation with an anode-cathode iron membrane and electrostatic repulsion	Fouling mitigation and extended membrane lifespan by 3x Increased sludge floc size and microbial diversity 66.70 % reduction in maintenance costs	(Yu et al., 2023)
Submerged Membrane Bioreactor (S-MBR)	Metal salts used: ferric chloride and aluminum sulfate	Improved P removal (94.23 %) Operational stability	(Silva et al., 2022)
Submerged Membrane Bioreactor (S-MBR)	Use of PVDF hollow fiber microfiltration membranes with 0.1 µm pore size Membrane operation with adjusted flows and regular cleaning procedures Associated with real treatment system with sequential biological reaction tanks: anaerobic, anoxic, and aerobic	High P removal efficiency (94.10 %) Effluent quality suitable for reuse and discharge (0.28 mg L^{-1}), meeting strict standards The system maintained high efficiency during operational variations and loads	(Smith et al., 2014)

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MBR configuration	**Applied process**	**Main advantages**	**Ref**
Membrane Bioreactor (MBR)	Point dosage of ferric sulfate in the MBR Comparison with continuous backwash upflow sand filter and high-rate compressible media filter technologies	The MBR achieved the highest P removal efficiency (95 %) among the evaluated technologies High solids removal efficiency	(Alibardi et al., 2021)
Membrane Bioreactor (MBR)	Addition of coagulants (PAC with varying basicities and alum) directly to the aerobic tank of the MBR	Meets discharge standards Proper use of coagulants helps control membrane fouling, extending lifespan and reducing maintenance costs Coagulant dosage can be adjusted based on inlet water quality and discharge requirements, providing operational flexibility	(Lee et al., 2017)
Conventional Membrane Bioreactor (C-MBR), Movable Biofilm MBR (MB-MBR), Anoxic/Oxic MBR (A/O-MBR)	Uses traditional suspended biomass (C-MBR) Incorporates Kaldnes® plastic media for biofilm growth (MB-MBR) Combines anoxic and oxic zones with Kaldnes® plastic media (A/O-MBR)	Reduced membrane fouling Increased P removal efficiency (69.7 %) Extended filtration cycles, especially in A/O-MBR	(Khan et al., 2014)
Side-Stream Aerobic Granular Sludge Membrane Bioreactor (AGMBR)	Use of a long anaerobic phase during the SBR cycle to promote P accumulation by PAOs The system operated with 240-min cycles, including 60 min of anaerobic filling, 170 min of aeration, and 10 min of settling and disposal	High P removal efficiency (≥ 95 %) Significant membrane fouling reduction due to granular structure and anaerobic feeding operation Simultaneous removal capacity for organic compounds and nutrients	(Iorhemen et al., 2018)
Multi-Anoxic/Oxic Anaerobic Membrane Bioreactor (An-M(A/O)-MBR)	Incorporation of multiple anoxic and oxic phases to promote effective nitrification/denitrification and biological P removal The system uses step-feed to optimize organic substrate distribution along the reactor	Operational flexibility through adjusting feed rates and anoxic/oxic zones to optimize nutrient removal Reduced membrane fouling due to design that allows effective solids retention and strategic aeration	(Yuan et al., 2015)

MBR configuration	Applied process	Main advantages	Ref
		Adaptability to different organic load levels, maintaining treatment efficiency even with significant variations in effluent concentration	
Intermittently Aerated Membrane Bioreactor (MBR-IA)	The MBR-IA system operates with alternating aerobic and anoxic phases to stimulate specific biochemical reactions for nutrient removal	Low sludge production and good effluent quality Potential for P recovery, reducing excess sludge discharge Energy savings due to intermittent aeration Ability to recycle P-rich sludge	(Wang et al., 2015)
Compartmentalized Anaerobic Bioreactor (ABR) combined with Membrane Bioreactor (MBR)	Multi-compartment configuration allowing microbial environments to be optimized for different treatment functions Use of sludge cycling and controlled dissolved oxygen conditions to maximize nutrient removal	Configuration allows for the use of different zones for specific processes (nitrification, denitrification, P release and absorption), promoting efficient treatment Operational stability with high-quality effluent production	(Wu et al., 2014)
Membrane Bioreactor (MBR) with ZeeWeed® 500D ultrafiltration	Hollow fiber membrane bioreactors operated by suction	Smaller footprint compared to conventional systems Superior effluent quality, suitable for various direct reuse applications, such as cooling tower makeup water Significant reduction in sludge production High P and SS removal efficiency	(Pagotto et al., 2014)
Moving Bed Membrane Bioreactor (MBMBR)	Combination of biofilm (IFAS) with a membrane bioreactor (MBR), using biofilm carriers in aerobic and anoxic reactors Use of sludge cycling and controlled dissolved oxygen operation to maximize nutrient removal Separate zones for effective nitrification and denitrification, as well as biological P removal by PAOs	Higher volumetric loading rates Flexibility in the anaerobic, anoxic, and aerobic mass fraction through liquid mix recycle Higher volumetric loading rates and lower sludge production due to higher SRT	(Mannina et al., 2018)

MBR configuration	Applied process	Main advantages	Ref
Pilot-Scale Membrane Bioreactor (MBR-P)	Operation under varying temperature conditions to investigate effects on nutrient removal (P1, P2, P3, P4, and P5) The UCT configuration helps maximize biological nutrient removal (nitrogen and P), and the MBR setup allows continuous operation without sedimentation issues	High efficiency in nitrogen and P removal, especially under varied temperatures. Capable of effective operation across a wide temperature range (25 – 40 °C). Flexibility in treatment due to modular configuration. Ability to adjust operational conditions in response to temperature and organic load.	(Sayi-Ucar et al., 2015)
Anoxic/Oxic Membrane Electro-Bioreactor (A/O e-MBR)	System operation with varying HRT to investigate effects on nutrient removal, biomass activity, and membrane fouling behavior. Includes a pre-denitrification tank to enhance total nitrogen removal in e-MBR systems, alternating anoxic and aerobic conditions through EC application. Application of EC between two metallic electrodes.	Reduced plant size due to integrated processes. High organic matter and P removal efficiencies, superior to those observed in C-MBR.	(Battistelli et al., 2018)
Submerged PVDF Hollow Fiber Membrane Bioreactor (SMBR)	Use of specially designed membranes for large-scale wastewater treatment. System capacity: 50 m^3 d^{-1}.	High removal efficiency and complete SS rejection. High phosphate removal efficiency, achieving between 80 – 85 % removal after a 4 – 5 d acclimation period.	(Ratanatamskul et al., 2015)
Anoxic and Aerobic Membrane Bioreactor (A/O-MBR)	Both systems configured with submerged membranes. Comparative process between a four-stage anoxic MBR and an aerobic MBR to avoid chemical use for nutrient removal.	Efficient carbon source utilization for nutrient removal. Greater operational control through distinct phases allowing fine adjustments in response to variations in input load and composition.	(Lee et al., 2015)
Anaerobic/Anoxic/Aerobic Membrane Bioreactor with Limited Aeration (AAO-MBR)	Combination of anaerobic, anoxic, and aerobic bioreactors in sequence to optimize nutrient removal.	MBR achieved nitrogen and P removal of 81.5 % and 96.7 %. Limited aeration AAO-MBR reduced fouling issues.	(Jiang et al., 2021)

MBR configuration	Applied process	Main advantages	Ref
	Limited aeration application to maintain optimal conditions for biological P release and absorption, as well as simultaneous nitrification and denitrification	MBR improved metabolic activity of bacteria responsible for nutrient removal. Resulting sludge has high reuse potential.	
Submerged Ceramic Membrane Bioreactor (SMBR) with Iron (Fe(II)) Addition and In-Situ Ozonation	In-situ ozonation applied intermittently, providing a simple approach to extend MBR operation with iron dosing	Ozonation improved mixed liquor properties and delayed severe fouling onset on membranes. Increased floc size and ozone membrane cleaning contributed to fouling control. 33 % reduction in membrane fouling compared to MBR with only Fe(II).	(Asif et al., 2021)
Submerged Membrane Bioreactor (SMBR) with Iron Addition and Acidogenic Co-Fermentation	MBR used with Fe(III) dosing for high P removal efficiency. Anaerobic co-fermentation applied to process sludge and recover soluble P. Recovery process included vivianite formation by adjusting supernatant pH.	Over 60 % of P in municipal wastewater recovered as vivianite. High P removal efficiency (95.6 % with $FeCl_3$ at 20 mg Fe L^{-1}). Significant reduction in inorganic accumulation in MBR, improving sludge activity and efficiency	(Li et al., 2018)
Submerged Membrane Bioreactor (SMBR) with Aluminum Sulfate Addition	Operation with varying influent COD concentrations to test the effect of COD/N ratio on nutrient removal and treatment efficiency, combined with aluminum sulfate addition for chemical P precipitation.	Sludge activity was not inhibited but slightly improved with aluminum sulfate addition. P removal was effectively enhanced by aluminum sulfate addition, achieving concentrations below 0.5 mg L^{-1}. Effective reduction in membrane fouling due to decreased EPS.	(Sun et al., 2019)
Conductive Moving Bed Membrane Bioreactor (EcMB-MBR)	System combining wastewater treatment with bio-electrochemical processes using conductive floating media and electrodes, operating in intermittent electrical exposure conditions	High nitrogen and P removal efficiency compared to conventional MBRs. Use of conductive media reduced energy consumption and improved contaminant removal.	(Udomkittayachai et al., 2021)

MBR configuration	Applied process	Main advantages	Ref
		Additional operational costs were reasonable, representing a 10 – 30 % increase over conventional MBR systems	
Inclined Tube/Oxidation Ditch Membrane Bioreactor (IT/OD-MBR)	Integration of an inclined tube anoxic compartment with an aerobic compartment equipped with microfiltration membranes. The system operates with variable horizontal flow rates (0.2, 0.3, 0.4 m s^{-1}).	P removal efficiency above 90 %. Capability to operate with low dissolved oxygen levels, saving energy. Reduced excess sludge through inclined tube zone. Capable of effectively treating wastewater with varying organic and nutrient loads. Potential for high-quality water recycling for landscape irrigation and toilet use	(Ratanatamskul and Romskul, 2022)
Anaerobic-Anoxic-Oxic Membrane Bioreactor System (A2O-MBR)	Membrane bioreactor coupled with an anaerobic sludge holding tank (SHT) to induce decoupled metabolism, operated with prolonged HRT and high MLSS. Recycled sludge introduced into the anaerobic sludge holding tank to limit substrate and oxygen availability	Significant reduction in sludge production due to decoupled metabolism, reducing sludge treatment and disposal costs. Maintained high P removal efficiency despite prolonged SRT.	(Na et al., 2017)
Membrane Bioreactor (Anaerobic + Oxic System) Combined with Dissolved Air Flotation (DAF)	DAF-MBR system using hydrophilic polyvinylidene fluoride (PVDF) microfiltration membrane with pore size 0.3–0.4 µm. DAF system used as a pre-treatment to reduce organic load and oily material before MBR treatment, operating without coagulant addition	Enhanced efficiency using DAF + MBR technology for SS and total P removal. Reduced membrane fouling due to oily material and SS removal by DAF	(Kim et al., 2015)
Membrane Bioreactor with Electrocoagulation (E-MBR)	MBR system combined with electrocoagulation (E-MBR), using different power supply conditions, including constant and variable voltage from solar panels	Higher nutrient removal efficiencies under higher voltage application. Mitigation of membrane fouling.	(Liu et al., 2019)

MBR configuration	Applied process	Main advantages	Ref
		Ammoniacal nitrogen and phosphate removal improved after electrocoagulation	
Hybrid Membrane Bioreactor (HMBR) and Conventional Membrane Bioreactor (C-MBR)	Operation included biocarrier use to support biofilm growth in HMBR compared to conventional MBR.	Biofilm addition helped maintain higher microbial concentration and diversity. HMBR showed greater nitrogen removal efficiency but was indifferent in P removal compared to conventional MBR	(Palmarin and Young, 2019)

Notes: MBR = Membrane Bioreactor; PAO = Phosphorus-Accumulating Organisms; EPS = Extracellular Polymeric Substances; EC = Electrocoagulation; SBR = Sequential Batch Reactor; HRT = Hydraulic Retention Time; SRT = Solids Retention Time; MLSS = Mixed Liquor Suspended Solids; SS = Suspended Solids; TMP = Transmembrane Pressure. Entries are organized by treatment category: electrocoagulation-assisted, coagulant-assisted, and zone-based/hybrid configurations.

5 Conclusions

This review set out to determine how operational parameters and reactor configurations govern phosphorus removal in MBR-based systems. Across 29 bench- and pilot-scale studies published between 2014 and 2025, the evidence shows that MBRs reach the stringent effluent P concentrations demanded by current discharge regulation, but that they do so through mechanisms whose performance depends sharply on the operating regime rather than on the membrane itself.

Configuration was the strongest determinant of performance. Electro-assisted and coagulant-assisted arrangements consistently exceeded 90 % TP removal, whereas conventional aerobic MBRs without a dedicated anaerobic zone or chemical dosing showed markedly more variable results. Among operational parameters, the balance between HRT and SRT, the availability and internal distribution of VFAs, and the aeration regime emerged as the controlling variables, since all three act on the anaerobic release and aerobic uptake sequence that underpins biological phosphorus removal. Temperature exerted a measurable effect, with efficiency falling from approximately 95 % at 24 °C to about 50 % above 35 °C. Conditions that improve phosphorus removal frequently accelerate membrane fouling, and this trade-off was observed across configuration types; recent work indicates, however, that it reflects the strategies conventionally adopted rather than a necessary relationship, since micro-granular sludge systems have achieved effluent TP below 0.03 mg L^{-1} with stable transmembrane pressure at short HRT.

Four limitations qualify these conclusions. The search was restricted to a single database, Scopus, for the reasons of metadata consistency set out in Section 2, and records indexed elsewhere may not have been retrieved. The included studies report phosphorus heterogeneously, some as total phosphorus and others as orthophosphate, which constrains direct comparison and means that reported TP removal may partly reflect the physical retention of particulate P rather than removal of dissolved P. The evidence base is dominated by bench- and pilot-scale work, and full-scale characterization is scarce, with no Brazilian case other than EPAR Capivari II documented in the peer-reviewed literature. Finally, cost and energy assessments were absent from most of the studies reviewed, although recent pilot-scale work reporting energy performance alongside removal efficiency indicates that this gap is beginning to close.

The contribution of this work lies in relating operational conditions to performance separately for each P fraction reported, and in setting out the mechanisms by which removal

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occurs rather than treating efficiency as a property of the configuration alone. This provides a basis on which subsequent studies can be compared, and clarifies which reported efficiencies are attributable to dissolved-P removal.

Future research should priorities standardized reporting metrics that distinguish phosphorus fractions explicitly, systematic cost and energy assessment alongside removal performance, characterization of full-scale installations and quantification of the recovery step that converts accumulated phosphorus into a usable product. The recent demonstration that fouling can be controlled through sludge morphology and microbial regulation rather than through chemical dosing identifies a route by which the central trade-off found in this review might be relaxed, and merits validation at larger scale and with real wastewater.

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Abbreviations

A	Ampere
An-MBR	Anaerobic Membrane Bioreactor
AAO	Anaerobic-Anoxic-Oxic
AAO-MBR	Anaerobic/Anoxic/Oxic Membrane with Limited Aeration
A/O	Anoxic/Oxic
A/O-MBR	Anoxic/Oxic Membrane Bioreactor
A/O e-MBR	Anoxic/Oxic Electro-membrane Bioreactor
ABR	Anaerobic Baffled Reactor
ABR-MBR	Anaerobic Baffled Reactor combined with Membrane Bioreactor
AGS	Aerobic Granular Sludge
AGS-MBR	Aerobic Granular Sludge-Membrane Bioreactor
AGMBR	Aerobic Lateral Flow Granular Sludge Membrane Bioreactor

C	Carbon
CA	Continuous Aeration
CAS	Conventional Activated Sludge
C-MBR	Conventional Membrane Bioreactor
DAF	Dissolved Air Flotation
DAF-MBR	Dissolved Air Flotation followed by Membrane Bioreactor
DAO	Deoxygenation-Anaerobic-Oxic
COD	Chemical Oxygen Demand
EC	Electrocoagulation
E-DMBR	Electric Dynamic Membrane Bioreactor
E-MBR	Electro Membrane Bioreactor
EcMB-MBR	Electroconductive Moving Bed Membrane Bioreactor
EPS	Extracellular Polymeric Substances
ET	Electric Tension
F	Flow
Fe(II)	Ferrous Ion
Fe/O_3-MBR	Fe(II)-dosed and In-situ Ozonation Membrane Bioreactor
$FeCl_3$	Ferric Chloride
GAO	Glycogen-Accumulating Organisms
H-MBR	Hybrid Membrane Bioreactor
LAC	Conventional Activated Sludge
IFAS	Integrated Fixed-Film Activated Sludge
IT-OD	Inclined Tubes-Oxidation Ditch
MB	Moving Bed
MB-MBR	Moving Bed Membrane Bioreactor
MBR	Membrane Bioreactor
MBR-IA	Membrane Bioreactor with Intermittent Aeration
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
NTU	Nephelometric Turbidity Units
NR	Not Reported
P	Phosphorus
PAC	Polyaluminum Chloride

PAOs	Phosphorus Accumulating Organisms
PF	Permeate Flow
pH	Potential of Hydrogen
PHA	Polyhydroxyalkanoate
PO_4^{3-}	Orthophosphate
PO_4^{3-} - P	Phosphate-Phosphorus
TMP	Transmembrane Pressure
SBR	Sequential Batch Reactor
SS	Suspended Solids
TSS	Total Suspended Solids
TP	Total Phosphorus
HRT	Hydraulic Retention Time
SRT	Solids Retention Time
V	Volts
VFA	Volatile Fatty Acids
WWTP	Wastewater Treatment Plants
SMEBR	Submerged Membrane Electro-Bioreactor
MBR/Fe/Ac	Membrane Bioreactor with Fe(II) dosing and Acidogenic Co-fermentation
An-M(A/O)-MBR	Anaerobic-multiple Anoxic/Oxic-Membrane Bioreactor
Pi-MBR	Pilot Membrane Bioreactor
Ae-MBR	Aerobic Membrane Bioreactor
IT/OD-MBR	Inclined Tube/Oxidation Ditch-Membrane Bioreactor
EPAR	Estação de Produção de Água de Reúso
SANASA	Sociedade de Abastecimento de Água e Saneamento

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