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Benefits of Wastewater Nutrient Treatment Upgrades for Removing Contaminants of Emerging Concern: A Systematic Review

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Executive Summary

Increasing regulatory requirements and aging infrastructure are leading to upgrades in wastewater treatment plants across the San Francisco Bay Area. These changes include additions to enhance nitrogen removal with significant interest in exploring whether these treatments can also improve the removal efficiency of contaminants of emerging concern (CECs). To do so, we have systematically reviewed and synthesized available studies that quantify the removal efficiency of CECs via advanced nitrogen removal technologies. This review provides an initial guide and broad insights into the potential for these technologies to provide regional water quality co-benefits.

To identify relevant studies, we searched across bibliographic databases and screened over 600 publication records using predefined eligibility criteria. Our screening prioritized treatment technologies with strong potential for regional adoption, ultimately incorporating 34 eligible studies into this systematic review. Chemicals were categorized into classes that closely reflected those in the tiered risk-based framework used by the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP). Data extracted included relevant metadata (e.g., treatment configuration, operational conditions) and quantitative data (e.g., influent and effluent concentrations of CECs) from each study. Pharmaceuticals were the most common CEC class studied (number of studies = 19), followed by antibiotics (grouped separately from pharmaceuticals for this report; $n = 13$), and bisphenols ($n = 12$). We broadly categorized different treatment configurations across papers into conventional activated sludge (CAS), the most common secondary treatment type with limited nutrient removal, and newer treatments, conventional biological nutrient removal (CBNR) and membrane bioreactors (MBR), which can more effectively eliminate nutrients. The most common treatment method in this review was MBR ($n = 28$), followed by CAS ($n = 18$).

We found significant variations in concentration-based removal between treatment configurations for various CECs. While not statistically significant, post-hoc comparisons revealed that MBR configurations achieved higher removal rates on average across all CECs (model-adjusted mean $67\% \pm 5\%$) than CAS ($57\% \pm 6\%$) and CBNR ($61\% \pm 7\%$). Although MBR demonstrated slightly better removal performance overall, these improvements occurred in only some CECs classes. Contaminants in the high concern tier (per- and polyfluoroalkyl substances [PFAS], organophosphate esters [OPEs]) had limited available data, with initial findings suggesting little removal of OPEs across any treatment and potential improvements for certain PFAS in MBR.

This systematic review suggests that potential water quality co-benefits can be achieved by upgrading older CAS systems to MBR treatment configurations, but only for select contaminant classes. Due to limited monitoring data, more studies preceding and following an upgrade are needed, particularly for high concern CECs (PFAS and OPEs).

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List of Acronyms

Acronym	Description
A/A/O-MBR	anaerobic/anoxic/oxic membrane bioreactor
A ² /O+OD	anaerobic/anoxic/oxic with an oxidation ditch
AD	aeration ditch
AnOMBR	anaerobic osmotic membrane bioreactor
AnOMBR-MD	anaerobic osmotic membrane bioreactor membrane distillation
AS	activated sludge
AS+N	activated sludge with partial nitrification and denitrification
ASBR	activated sludge bioreactor
BAF	biological aerated filter
BF	biofilter (non-aerated)
BFa	biofilter (aerated)
BNR	biological nutrient removal
CA+F	chemical addition and filtration
CAS	conventional activated sludge
CAS-N	nitrifying activated sludge
CAS-TT	conventional activated sludge with tertiary treatment
CBNR	conventional biological nutrient removal
EBNR	enhanced biological nutrient removal
EBNR+F	enhanced biological nutrient removal with chemical addition and filtration
EBNR+MF	enhanced biological nutrient removal with membrane filtration
FO	forward osmosis
GAC	granular activated carbon filtration (non-aerated)
GACa	granular activated carbon filtration (aerated)
HRT	hydraulic residence time
IFAS-MBR	integrated fixed-film activated sludge membrane bioreactor
MABR	membrane aerated bioreactor
MBBR+DAF	moving/mixed-bed bioreactor with dissolved air flotation
MBMBR	moving bed membrane bioreactor
MBR	membrane bioreactor
MBR-FS	membrane bioreactor with flat sheet module
MBR-HF	membrane bioreactor with hollow-fibre module
MBR+O ₃	membrane bioreactor with partial flow ozonation

Acronym	Description
MIEX	magnetic ion exchange
MLE	modified Ludzack-Ettinger process
MUCT	modified University of Cape Town process
PAC	powdered activated carbon
RSF	rapid sand filtration
SRT	sludge retention time
SST	secondary settling tank
WWTP	wastewater treatment plant

1. Introduction

1.1. Overview of Nitrogen-Reduction Treatment Technologies

San Francisco Bay is a highly nutrient-enriched estuary, with the majority of its nutrient inputs originating from treated effluent discharged by 37 wastewater treatment plants (WWTPs). Although these nutrients are vital for a healthy ecosystem, excessive levels can degrade water quality and destabilize habitats by fueling rapid phytoplankton growth, depleting dissolved oxygen, and triggering harmful algal blooms. In response to these growing nutrient-related challenges, the San Francisco Bay Nutrient Management Strategy (NMS) was launched in 2012. The mission of the NMS is to cultivate a comprehensive understanding of nutrient dynamics to guide effective, science-based management and policy decisions (San Francisco Estuary Institute, 2025). These scientific initiatives have already informed major regulatory milestones, including the implementation of a regional permit governing effluent discharges from the 37 wastewater agencies across the Bay.

To combat nutrient pollution, particularly nitrogen, WWTPs throughout the San Francisco Bay Area are planning and implementing major technology upgrades. Interestingly, many of the advanced technologies deployed for nitrogen removal may concurrently enhance the reduction of contaminants of emerging concern (CECs), potentially yielding dual environmental benefits. However, there is still a critical gap in our understanding of how these nitrogen-focused upgrades affect the fate and removal of CECs, which continue to present risks to aquatic ecosystems and human health.

The conventional activated sludge process (CAS) is the most widely used secondary treatment process for urban and industrial wastewater in the US and globally. The activated sludge process was discovered in the early 1900s and relies on providing microorganisms with oxygen (via aeration) to support the breakdown of organic matter. The activated sludge process uses an aeration tank followed by a secondary settling tank, where a portion of the sludge is returned to the aeration tank to maintain a high concentration of microorganisms. The remaining sludge is removed, dewatered and then used in anaerobic digestion or as biosolids for beneficial reuse. As an alternative conventional secondary configuration, trickling filters function by continuously spraying wastewater over a bed composed of coarse media, such as plastic or rocks. As the water trickles through this setup, organic matter is broken down by a biological slime layer that develops on the media. Most of the facilities in the Bay Area rely solely on CAS, trickling filters, or a combination of the two, without any supplementary treatment (BACWA, 2024).

Nutrient removal rates via CAS are heavily influenced by the sludge retention time (SRT), which is a measure of the average time that microorganisms remain in the

treatment process. Previous studies have shown that SRT is positively associated with nutrient removal (Bothfeld, 2021; Clara et al., 2005; Lubliner & Ragsdale, 2010; Stephenson & Oppenheimer, 2007). Clara et al. (2005) also found that biodegradable CECs have a corresponding SRT critical value, whereas any facility with a lower SRT will not effectively remove the corresponding CEC. However, operating a CAS treatment configuration at high SRTs necessary to achieve nutrient removal requires significant amounts of oxygen and energy (Ekholm et al., 2023). Season changes and precipitation also affect nutrient removal rates (Oller et al., 2014).

To enhance their efficiency in nutrient extraction, wastewater treatment facilities have implemented conventional biological nutrient removal (CBNR) systems. This upgrade to traditional secondary treatment methods utilizes nitrification and denitrification processes to convert nitrogen compounds into benign nitrogen gas, while simultaneously trapping phosphorus within the sludge for removal (Bothfeld, 2021). They are typically constructed with a sequence of anaerobic-anoxic-aerobic reactors, and then a secondary clarifier. A modification to this treatment train is the Modified Ludzack-Lettinger (MLE) process, which implements four individual stages (anoxic, aerobic, clarifier, and an internal recycle loop) and is one of the most widely implemented biological treatment methods (Capodaglio et al., 2016). A growing share of the Bay Area WWTPs utilize some form of nitrification-denitrification (BACWA, 2024).

More advanced BNR treatment technologies have been developed to overcome challenges associated with CAS treatment processes, such as the space required (Asante-Sackey et al., 2022) and increasing the SRT (Al-Asheh et al., 2021). A membrane bioreactor (MBR) is one of these technologies, which uses a two-stage process for elimination of organic contaminants and nutrients; microbial degradation via activated sludge and low-pressure membrane filtration, using either microfiltration or ultrafiltration techniques (Al-Asheh et al., 2021; Cases et al., 2011; Radjenović et al., 2009). An MBR removes contaminants via physical retention, sorption, biodegradation, and air stripping (Cotton et al., 2024). Membrane Aerated Biofilm Reactors (MABR) differ from MBRs in that oxygen diffuses through a gas permeable membrane into a biofilm, where contaminants are then oxidized (Lakshminarasimman et al., 2026; Veolia, 2025). These are an example of a “drop-in fixed growth system,” suitable for upgrading existing tanks without completely replacing clarifiers. Presently, MBRs have been fully deployed at only a few Bay Area wastewater treatment facilities (BACWA, 2024).

1.2. Contaminants of Emerging Concern

Broadly characterized, contaminants of emerging concern (CECs) are naturally occurring or synthetic chemicals that lack adequate or any regulation, are typically omitted from routine environmental monitoring, and possess the capacity to infiltrate the environment, potentially resulting in detrimental effects on human health or ecological

systems. The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) has monitored various CECs across the Bay environment including bird eggs, bivalves, harbor seals, prey fish, sport fish, sediment, surface water, stormwater, and wastewater (Sutton et al., 2024). A variety of CECs have been examined including per- and polyfluoroalkyl substances (PFAS), organophosphate esters (OPEs), microplastics, pesticides, bisphenols, tire- and vehicle-derived contaminants, pharmaceuticals, and personal care and cleaning product ingredients. For CECs found to occur in the Bay, the RMP establishes priorities using a tiered risk-based framework with categorization primarily based on comparison of observed concentrations to available toxicological thresholds. CECs within this framework and bioassays were prioritized for this project to systematically review the removal capabilities of nitrogen-reduction treatment technologies. Brief summaries of key contaminants identified in the review are shown in Table 1 with further information provided in Sutton, et al. 2024.

Table 1. Brief summaries of key contaminants identified in this review which are categorized as a part of the RMP's tiered risk-based framework.

Contaminant Class	RMP CEC Risk-Tier	Chemical Properties	Notable Sources
OPEs	High	• Water-soluble • Partition to sediment • Semi-volatile and can be transported long distances • Metabolized; limited bioaccumulation • Partially biodegradable; halogenated variations are persistent	Used as flame retardants and plastic ingredients for consumer and industrial products including furniture, construction materials, textiles, electronics
PFAS	High	• Water-soluble • Partition to sediment • Some are semi-volatile and can be transported long distances • Persistent; precursors degrade to persistent PFAS • Bioaccumulation significant, particularly for long-chain compounds	Used in fire-fighting foams, carpet treatments, grease and water-resistant coatings for clothing and food packaging, processing aids in electronics and polymers, paper manufacturing including toilet paper, cosmetics and personal care products, paints, construction materials; use in some products has been banned in California

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Contaminant Class	RMP CEC Risk-Tier	Chemical Properties	Notable Sources
Bisphenols	Moderate	• Water-soluble • Partition to sediment • Lower volatility • Metabolized; Limited bioaccumulation • Some variations show partial biodegradability	Used in polycarbonate plastics, epoxy resins, thermal paper, flame retardants, tires, textiles, paints and coatings
Microplastics	Moderate	• Physical particles that transport chemical ingredients and transformation products • Wide-ranging sizes, morphologies, surface areas, densities, and chemical characteristics • Persistent	Derived from tires, textile fibers, litter, and various other sources
Antibiotics	Low	• Inherently toxic, contribute to antimicrobial resistance • Vary in water versus lipid solubility depending on functional groups • Some are persistent	Includes prescription and over-the-counter medications
Ethoxylated Surfactants	Low	• Water solubility increases as the number of ethylene oxide functional groups increase • Alcohol ethoxylates biodegradable with limited bioaccumulation, others are more persistent	Used in personal care and cleaning products as emulsifiers, pesticides to improve chemical stability, textiles, concrete, tire rubber, and others
Personal Care and Cleaning Product Ingredients	Low	• Broad class; Wide-ranging physicochemical properties, partitioning behavior, persistence, and bioaccumulation potential	In common consumer items, encompasses detergents, surfactants, fragrances, emulsifiers, acrylates, ultraviolet absorbers, antioxidants, and preservatives
Pharmaceuticals	Low	• Broad class; Wide-ranging physicochemical properties, partitioning behavior, persistence, and bioaccumulation potential	Covers prescription and over-the-counter medications, diagnostic agents, vitamins, and dietary supplements.

Contaminant Class	RMP CEC Risk-Tier	Chemical Properties	Notable Sources
4-methylphenol	Possible	• High water solubility • Low bioaccumulation potential • Biodegradable	Used in preservatives, to formulate antioxidants, and other products such as lubricating oils, motor oils, rubbers, and food products
Other Plastic Additives	Possible	• Broad class; Wide-ranging physicochemical properties, partitioning behavior, persistence, and bioaccumulation potential	Plastics in consumer products, commonly antioxidants, flame retardants, plasticizers, UV stabilizers, and colorants
Tire- and Vehicle Derived Contaminants	Possible	• Broad class; Wide-ranging physicochemical properties, partitioning behavior, persistence, and bioaccumulation potential	Tire and vehicle products, commonly used as vulcanization accelerators, crosslinking agents, corrosion inhibitors, antidegradants and antioxidants, and plasticizers

1.3. Bioassays and Toxicological Endpoints

An alternative to traditional target analysis of multiple chemical classes is assessing toxicological endpoints. For example, bioassays can serve as effect-based monitoring tools because they provide an estimate of the total biological impact (or cumulative effect) of complex wastewater mixtures with numerous CECs (Neale et al., 2020). *In vitro* bioassays can detect possible biological effects that may not be predictable primarily from a traditional target-based chemical analysis. Bioassays can be used to quantify (anti)estrogenic and (anti)androgenic effects (in addition to other hormones, e.g., hypothalamo–pituitary-thyroid axis hormones) which can be caused by a complex mixture of contaminants, for example endocrine-disrupting compounds (EDCs). Beyond endocrine disruption, *in vitro* bioassays can also detect oxidative stress biomarkers, immunotoxicity, neurotoxicity, while the aryl hydrocarbon receptor (AhR) bioassay can detect the environmental impacts of aromatic hydrocarbons. Testing both chemical composition and biological effects in aqueous samples can provide a holistic view of the compounds present that may not be apparent with just one or the other. For example, estrogenic compounds (e.g., some pharmaceuticals) can be masked out by anti-estrogenic compounds (e.g., some OPEs; Itzel et al., 2018). Hence, *in vitro* bioassays can be a powerful tool to quantify the effectiveness of nitrogen-reduction technologies in WWTPs.

1.4. Objective of this Review

The plan for the literature review of the potential co-benefit of nitrogen reduction technologies on CECs was directly informed by meetings with key stakeholders. Several meetings with members from the Bay Area Clean Water Agencies and San Francisco Bay Regional Water Quality Control Board helped guide eligibility criteria and data extraction, as well as inform the narrative and quantitative synthesis. These meetings identified (1) nutrient-reduction technologies to include; (2) the CECs of interest to include; and (3) the scale of the studies. Stakeholders also provided reports and references as part of an initial review. These benchmark references were used to guide the eligibility criteria and the data extraction and coding strategy.

The primary focus of this report is to systematically review and synthesize studies that quantify the removal efficiency of emerging contaminants of advanced nitrogen removal treatment technologies currently used or considered for adoption by Bay wastewater treatment plants. The primary research question is: How effective are these advanced treatment technologies in wastewater treatment plants at mitigating the fate and concentration of emerging contaminants? This question was structured using the population, exposure, outcome (PEO) model (Booth et al., 2019):

- Population: Wastewater Treatment Plants
- Exposure: Implementation of nitrogen removal technologies (Table A2)
- Outcome: Quantify removal of CECs

2. Systematic Search of Literature

2.1. Search String and Bibliographic Databases

Articles were found using the Web of Science bibliographic database to search on topic words (i.e., abstract, title, and key words). Searches were limited to the time period 1900 - 2026 (Table 2). Additional papers were identified through Google Scholar searches, and grey literature reports were provided by stakeholders involved in the scoping of the review. We evaluated search comprehensiveness by testing our search string using benchmark references (n = 4). Because including “membrane bioreactor” vastly increased search sensitivity (n > 6,000 papers vs. ~600 without) we managed the volume by filtering the larger 6,000-paper dataset specifically for mentions of bioassays.

Table 2. Search string used to search bibliographic databases for relevant studies. Component categories between search terms will be merged using "AND" Boolean operator, while "OR" will be used within categories. The asterisk (*) is a truncation wildcard character representing any number of characters.

Population	Exposure	Outcome	
biosolid*, sludge*, waste*, “wastewater treatment plant*”, WWTP, “sewage treatment plant”, sewage*, “waste sludge*”, effluent, influent, “publicly owned treatment work*”, POTW	“Conventional Biological Treatment Removal”, “Drop-in fixed growth systems”, “Modified Ludzack-Ettinger”, “Membrane Aerated Biofilm Reactor”, “removal technolog*”, “membrane bioreactor**	Benefit*, load, removal, reduce, increase, control, concentration, bioassay	PFAS, PFOA*, PFOS*, PFCA, PFNA, PFHxA, PFSA*, HFPO-DA, GenX, ADONA, “organophosphate ester*”, OPE*, TDCIPP, TCPP, triphenyl phosphate, TPhP, TBOEP, pharmaceutical*, micropollutant*, “organic pollutant*”, “emerging contaminant**

2.2. Article Screening and Study Eligibility Criteria

The eligibility criteria for this review differed slightly depending on the stage of the screening process. At the Title-Abstract screening phase, the exclusion criteria were as follows:

- Studies done outside of WWTPs (i.e., bench-top lab studies) were excluded
- Studies that did not measure at least one CEC or bioassay were excluded
- Studies that did not implement a treatment technology of interest were excluded (Table A2)

During the full-text screening phase, the exclusion criteria was as follows:

- Studies that were at the lab or bench-scale were excluded.
- Studies that did not measure a CEC explicitly named in the tiered risk-based framework or use toxicological endpoints (e.g., bioassays) were excluded.

2.3. Data Extraction and Coding Strategy

In addition to the study identification (e.g., first author, publication year, DOI), experimental meta-data and quantitative results were extracted from each study (Table 3). Experimental meta-data included the scale of the study (e.g., pilot or full-scale), the daily treatment capacity (if full-scale study), hydraulic residence time (HRT), sludge retention time (SRT), operational parameters (e.g, pH, temperature, DO), and the specific treatment technology assessed. Quantitative data extracted from each study included the broad category of CEC, the specific CEC, the matrix sampled, and the specific measurement. For the specific measurement, this could either be the raw concentration value or the percent removal. For the studies that did not provide percent removal values, these were calculated manually using provided concentration data. Data that were not reported in the study were coded as not reported (NR).

An AI driven pipeline was used for data extraction. PDFs of each study were uploaded to Google's NotebookLM, a closed system AI that grounds its responses to documents uploaded by the user, and provides hyperlinks in the original text indicating where data came from. It does not guess or pull from its broader training data. NotebookLM is more likely to omit data that is present in the paper than hallucinate numbers. We manually verified the data extracted from select studies before proceeding with the full review and quantitative analysis. We double checked AI provided numbers with in-text tables and figures for accuracy. Quantitative data was verified by following hyperlinks within the PDF. Because the AI only used terminology of the authors, terms were later standardized (e.g., m3/day was changed to m3/d; A/A/O-MBR was changed to A2O-MBR) to support data analysis and interpretation.

Table 3. Meta-data extracted from each identified study.

Variable	Description
Location	State or country where study conducted
Experimental Unit	Used to differentiate multiple WWTPs reported
Daily treatment capacity	Volume of sewage processed
Scale	Scale of treatability study (e.g., Lab vs. Pilot vs. Full-Scale)
Hydraulic Residence Time (HRT)	Average length of time that discrete quantity of WW remains within a treatment system

Variable	Description
Sludge Retention Time (SRT)	Average time that bacteria remain inside a biological reactor
Operational parameters	DO, pH, temperature
Treatment technology	Treatment technology tested
Category	Broad category of parameter measured (e.g., oxygen demand, sediment, nutrients, broader CEC class)
Parameter	Specific parameter measured (e.g., nitrogen species, specific CEC compounds)
Sample Size	# of samples taken for measurement
Matrix	Matrix sampled (e.g., influent, effluent, sludge)
Measurement Type	Type of measurement (e.g., average concentration, % removal)
Value	Number associated with measurement type
Unit	Unit associated with measurement (e.g., mg/L, ug/L, ng/L, %)
Data Qualifier	Used to differentiate data extracted from a table vs. estimated from a figure (E)

2.3.1. Categorization of Different Treatment Technologies

Terminology for technologies differed among studies, thus we grouped categories into conventional activated sludge (CAS), conventional biological treatment removal (CBNR), and membrane bioreactors (MBR). The goal of this categorization was to compare removal rates for these broad treatment categories and also simplify the results for interpretation and statistical analysis. This allowed us to rigorously compare broader CBNR treatment (e.g., MLE) and traditional CAS with the more advanced BNR treatment configurations (e.g., MBR). Some studies also included tertiary treatment following CAS, CBNR, and MBR. Those related to CAS with tertiary treatments were categorized as CBNR while for the other two categories they did not receive separate categorizations (Table A2). For example, three MBR studies (out of 16 total) would have been categorized as MBR + tertiary treatment. We conducted a sensitivity analysis and model results (i.e., statistical significance) did not change by discretizing MBR and MBR + tertiary treatments. Any data focused on a particular part of the wastewater treatment process (e.g., secondary settling tank, grit chamber, mixed processes) were generally excluded from analysis. See Table A2 for the list of original treatment technologies and the new treatment categorization.

2.4. Articles and Studies

A total of 34 studies are included in this systematic review. 635 studies were found by searching Web of Science, which includes 614 papers from the search omitting “membrane bioreactor” and 21 papers selected from the larger “membrane bioreactor”

and “bioassay” subset. 28 studies were found through a Google Scholar search and/or provided by stakeholders. Only original research articles were included, however review papers were screened for relevant studies and identified 28 additional studies to be screened in full-text, for a total of 128 articles screened for full-text. Common reasons for exclusion during full-text screening include other variations of wastewater treatment, or that they did not monitor a CEC. Full-text screening resulted in 34 studies being selected for data extraction with 25 being used for quantitative analysis (Figure A1).

2.5. Statistical Analysis

To determine if removal rates differed between treatment categories and across CEC classes, we fit a fixed-effects linear model with an interaction term (Treatment and CEC class as factors) using StudyID as a random effect using `lmer()` in R. The random effect accounts for study-level background factors by calculating a unique baseline for each paper to isolate the true effect of different treatment configurations on CEC classes. We incorporated data from all studies that had reported removal rates, or reported concentrations for influent and effluent to calculate removal rates ourselves. Data from the 4-methylphenol CEC class was excluded from the statistical model due to insufficient sample size ($n = 1$) while data from the remaining CEC classes (Table 4) were included. We evaluated statistical significance at an alpha level of 0.05. To identify differences between our factors, we calculated contrasts using `pairs()` and a Šídák adjustment for each significant main effect, which uses estimated marginal means. Estimated marginal means are model-predicted average values of a dependent variable (e.g., treatment) and account for differences in sample sizes for different groups.

We explored other variables (see Table 3) that might explain variation in removal rates based on previous research (e.g., SRT being positively related to nutrient removal and biodegradable CECs having an associated critical SRT value) or stakeholder input (co-benefits of N and CEC removal). However, only 6 studies (out of 34) reported N removal rates (i.e., $\text{NH}_4\text{-N}$, $\text{NH}_3\text{-N}$, NH_3 , or TN) and we found no relationship ($R^2 = 0.03$) between N removal rates and CEC removal. While 17 studies reported either a single SRT value or a range of SRT values across treatment configurations (see Table A1), plotting SRT against CEC removal revealed no apparent relationship ($R^2 = 0.008$), characterized by large within-study variability at single SRT values. Similarly, comparing SRT and influent concentrations yielded no apparent relationship ($R^2 = 0.007$). Given our limited dataset and our primary objective of comparing performance across treatment configurations, we constrained our fixed-effects linear model to the chemical classes and the treatment categories.

Table 4. Number of studies for each treatment category and contaminant class along with bioassays. Note that these are not unique studies, this is the number of studies that assessed effectiveness. For example, if one study measured removal rates in more than one treatment, that counts as 1 study each for that treatment category.

Contaminant Class	RMP CEC Risk-Tier	# of Compounds Included	CAS	CBNR	MBR
OPEs	High	3	2	2	2
PFAS	High	8	1	1	1
Bisphenols	Moderate	11	7	4	10
Microplastics	Moderate	9	2	1	3
Antibiotics	Low	40	10	6	15
Ethoxylated Surfactants	Low	11	5	3	6
Personal Care and Cleaning Product Ingredients	Low	22	5	2	7
Pharmaceuticals	Low	99	10	5	16
4-methylphenol	Possible	1	1	0	0
Other Plastic Additives	Possible	6	4	2	4
Tire- and Vehicle Derived Contaminants	Possible	6	3	1	3
Bioassays	NA	NA	6	3	6

3. Overview of Studies

Membrane bioreactors (n = 28) were the most common treatment identified in our systematic review, followed by CAS (n = 18) and CBNR processes (n = 11). 24 (out of 34) studies compared the effectiveness of two or greater treatment processes, with a comparison of CAS with MBR being the most common combination. 27 studies collected data from a full-scale WWTP, while 18 studies collected data from pilot-scale treatments. Studies primarily collected manual grab samples (n = 13) and composite samples (n = 17). The overall analytical methods targeting specific CECs varied among studies, with multi-target chemical analysis using solid-phase extraction (SPE) followed by liquid chromatography-tandem mass spectrometry (LC-MS/MS) being the most common. The full list of studies including this information is shown in Table A1.

Pharmaceuticals were the most common CEC class, with at least one being reported in 19 studies, followed by antibiotics (grouped separately from pharmaceuticals for this report; n = 13), and bisphenols (n = 11). Three papers reported removal rates for OPEs, and one paper for PFAS. Pharmaceuticals were the chemical class with the highest number of unique compounds, followed by antibiotics, and personal care and cleaning product ingredients (Table 4). The chemical classes in the low concern tier had more studies (and thus more data points) than chemical classes in the high and moderate concern tiers. Chemical classes in the possible concern tier had fewer studies and compounds than the other classes. Overall, the placement within the tiered risk-based framework also reflects data availability, highlighting the need for additional monitoring of chemical classes in the high and moderate concern tiers.

Given that PFAS is a CEC of high-priority, it is important to understand how PFAS might be removed through different treatment technologies. Choi et al., 2022 compared the effectiveness of three separate treatment trains (CAS, A2O-MBR, MLE) receiving the same influent. They estimated percent removal for all CECs measured (e.g., pharmaceuticals, hormones, pesticides, PFAS), and found that on average CAS, MBR, and MLE removed 85%, 96%, and 92% of CECs. However, when examining the 8 PFAS individually, we found that average removal rates (estimated using effluent concentrations prior to tertiary treatment) were much lower: 16% for CAS, 28% for MLE, and 44% for the MBR. Notably, PFOS removal rates for MLE (62%) and MBR (42%) were higher than for PFOA (16% and 13%, respectively). Three PFAS (PFPeA, PFHxA, and PFHpA) also showed notable increases in concentration following anoxic treatment in the MLE, and after aerobic treatment in the MBR (Figure 1). PFHpA also showed a high increase after the second aerobic treatment in MLE. More monitoring during different wastewater treatment processes is needed to quantify the fate of PFAS compounds through WWTPs, as many are likely sorbing onto sludge and/or transforming into PFAS compounds not currently measured analytically.

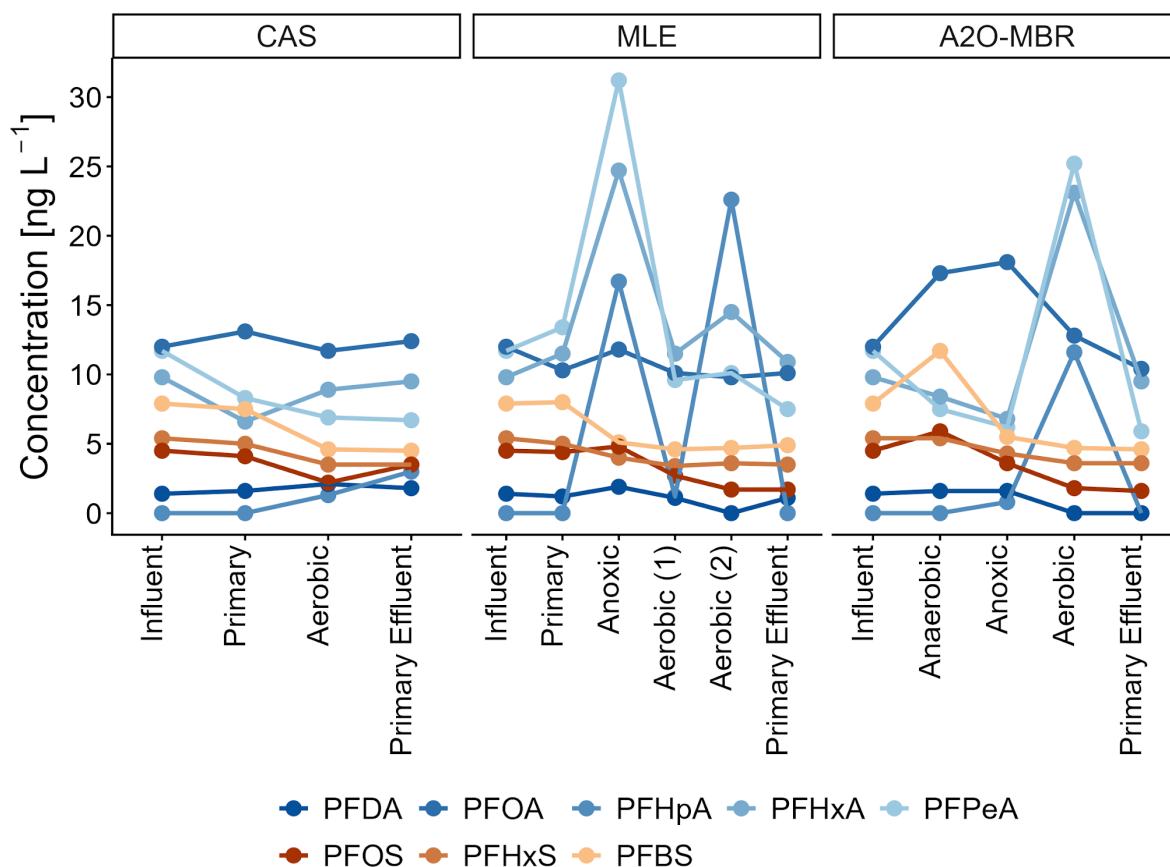


Figure 1. PFAS concentrations in three separate treatment trains. Data from Choi et al., 2022. PFCAs are blue, while PFSA are orange. Color shading decreases with chain length.

Our search identified three studies (Bayo et al., 2020; Lares et al., 2018; Lv et al., 2019) that monitored microplastic concentrations in MBR and CAS systems. Total microplastic removal was higher in CAS (98%, Lares et al., 2018) than in MBR (79%, Bayo et al., 2020). Bayo et al. (2020) suggested that the higher pressure in an MBR could explain why removal rates were lower. Leslie et al. (2017) suggested that long fibers could pass longitudinally through the MBR due to the high pressure applied, and that a decrease in performance of MBRs could also explain poor removal rates, but that additional research is needed. There were also differences in removal rates depending on the metric chosen (Lv et al., 2019), with higher removal rates being achieved when assessing mass, rather than total number of particles. The total amount of microplastics can increase when larger particles are broken during the grit removal process. Differentiating the fate of microplastics in WWTP requires sampling at several points throughout the treatment train and quantifying different metrics (e.g., total number of fibers vs. total mass). Wastewater treatment plants in the Bay (Mason et al., 2016) observed that tertiary filtration treatments were not effective at removing microplastics,

but additional research is needed to determine if these observations are consistent across similar treatment technologies at different facilities.

While MABRs have attracted growing interest, research evaluating their capacity to eliminate key CECs remains sparse. A Canadian study (Potvin et al., 2012) showed that an MABR system achieved a 65% removal efficiency for tetrabromobisphenol A in synthetic wastewater. This performance falls at the lower end of the efficiency range typical for conventional membrane bioreactors (MBRs) treating actual influent (62–90%). More recently, Lakshminarasimhan et al. (2026) evaluated the effectiveness of a full-scale hybrid MABR coupled with CAS across various weather conditions before and after upgrading. Their investigation of 20 organic micropollutants, primarily pharmaceuticals, indicated that 65% of the target compounds showed lower concentrations post-upgrade. Notably, bisphenol A removal rose substantially under warm weather conditions, from 44% prior to the upgrade to 93% afterward. Expanded research analyzing a broader spectrum of target CECs is needed to thoroughly benchmark MABR performance against alternative nutrient removal technologies.

Studies that assessed CEC removal using toxicological endpoints (n = 8) typically used a comprehensive battery of *in vitro/in vivo* bioassays, such as the Yeast Estrogen Screen (YES) and Yeast Androgen Screen (YAS). Parker et al. (2014), in warm conditions, and Pileggi et al. (2011) found CBNR to be generally more effective in reducing estrogenic activity (93-97%) compared to CAS (67-85%). Vålitalo et al., (2017), Bertanza et al. (2022), and Schneider et al. (2020) used various bioassays such as those to measure androgenic, estrogenic, and genotoxic activity in CAS and MBR treatment configurations, generally finding better removal of estrogenicity in MBRs. Though, Vålitalo et al., (2017) also found MBR performed worse in genotoxicity tests compared to CAS and Schneider et al., (2020) found higher anti-estrogenic activity. One of the studies found comparable reductions in CAS, CBNR, and MBRs with removal of estrogenicity around 96% (Drewes et al., 2005). These results suggest that MBR may be useful to reduce harmful activity, though more studies are needed to comprehensively assess different treatment processes with various bioassays that quantify effects beyond (anti) estrogenic/androgenic activities (e.g., neurotoxicity, immunotoxicity, biomarkers, and others).

4. Quantitative Synthesis of Treatment Technologies

We included data from all contaminant classes (Table 4) in our statistical analysis (with the exception of 4-methylphenol due to insufficient sample size). A Type II ANOVA (Table A3) revealed a significant interaction between CEC class and treatment configuration ($p = 0.002$) and a significant main effect for CEC class ($p = 0.0002$), while the treatment configuration main effect was not significant ($p = 0.079$). These results indicate that contaminant removal rates depend on the specific treatment configuration and vary across different contaminant classes, suggesting that nutrient co-benefits are limited to select groups.

There were several differences among CEC classes (Figure 2) with antibiotics and other pharmaceuticals having higher removal rates in CBNR and MBR treatment configurations compared to CAS. Although derived from a single study and not uniform across all compounds, PFAS as a class demonstrated a similar increase in removal rates from CAS to MBR treatment configurations.

Tire- and vehicle-derived contaminants (specifically, benzothiazoles and benzotriazoles) showed a different correlation of improved removal rates when comparing MBR and CAS, though CBNR treatment notably increased the levels of these contaminants. Although, it should be noted that only one study (Choi et al., 2022) measured tire- and vehicle-derived contaminants in a CBNR treatment. The authors measured 1-Hydroxy-benzotriazole (HOBt) and tolyltriazole (TTR), and saw large increases (> 200% increase in effluent compared to influent) in TTR in three different treatment configurations (CAS, A2O-MBR, MLE), which the authors attributed to their low biodegradation constants, desorption from sludge, or possible transformation. However, past work on free and bound benzotriazoles in sediment (Reddy et al., 2000), suggests these compounds might be chemically bound to sediment. The increase in TTR could be explained by sediment-bound compounds in raw wastewater influent being released during the treatment process.

Other classes, such as OPEs, bisphenols, and personal care and cleaning product ingredients had similar removal rates across treatment configurations, suggesting that other treatment methods are needed to achieve improved contaminant removal. This is of particular concern for OPEs, which are being consistently removed at the low levels in all treatment technologies. And, some classes had lower removal rates in MBR and CBNR treatments compared to CAS (e.g., microplastics, ethoxylated surfactants, and other plastic additives). However, because the chemical classes with lower MBR removal rates were generally evaluated using fewer studies and compounds (Table 4), further monitoring data is essential to establish whether these outcomes are due to inherent monitoring variability or poor treatment performance.

Benefits of WW Nutrient Treatment Upgrades for Removing CECs - FINAL

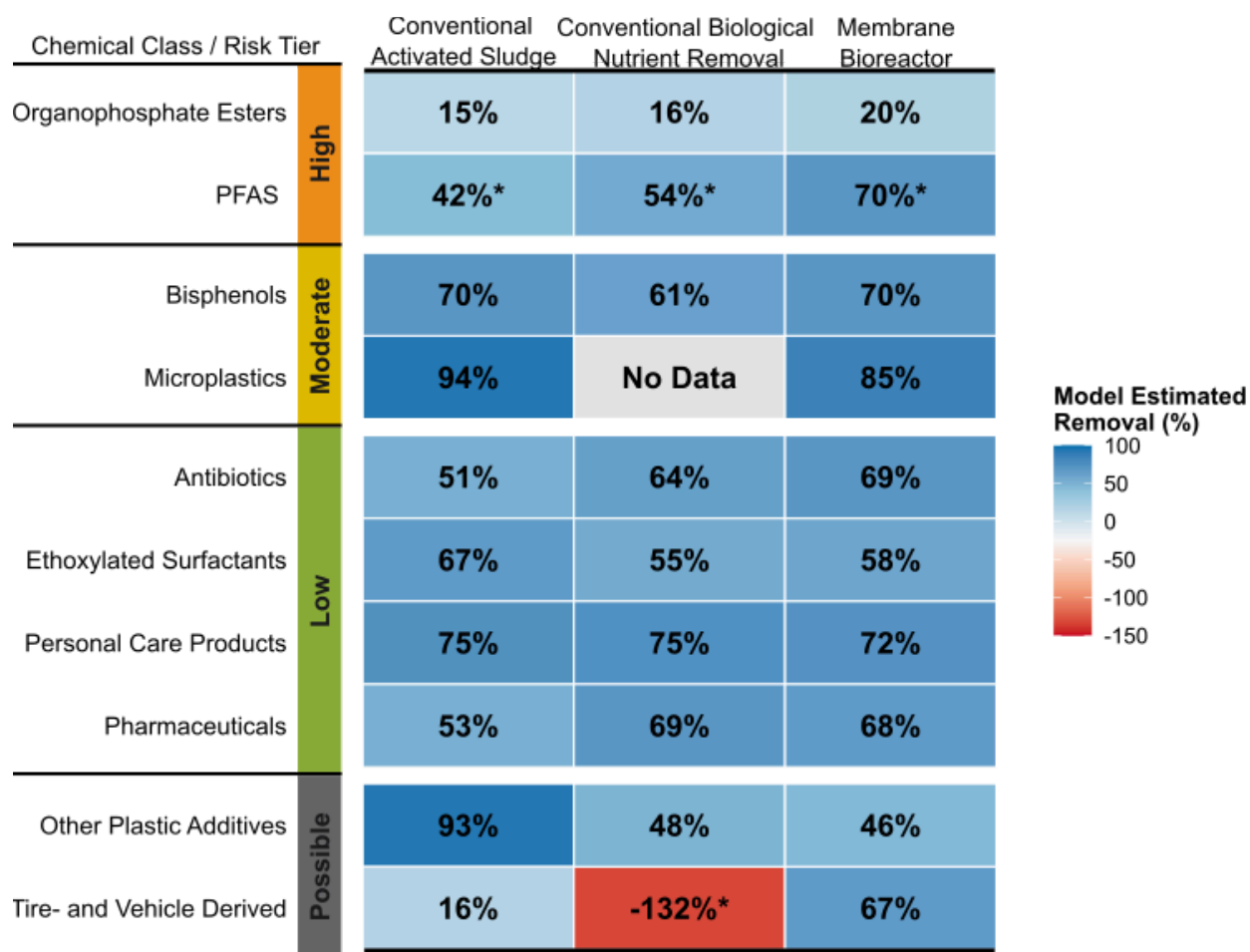


Figure 2. Estimated Marginal Mean (EMM) concentration removal rates (from influent to effluent) for each contaminant class and treatment configuration.

* = data from a single study.

While not significant, we estimated the overall removal rates of the different treatment configurations (Table A4) through post hoc analysis (using a Šídák adjustment). We then assigned pairwise grouping letters to indicate which chemical classes or treatment configurations had significantly different removal rates. Overall removal rates (for all contaminant classes) were 57%, 61%, and 67% for CAS, CBNR, and MBR treatment configurations (Figure A3). While not significant, there are slightly higher overall removal rates of CEC classes for MBR treatment configurations. Similarly, we estimated overall removal rates (irrespective of treatment) for each chemical class (Table 5, Figure A4). Due to the inherent variability in these studies, there is still a high degree of uncertainty (indicated by large confidence intervals) in our model-derived estimates of the removal rates for each chemical class. Generally, contaminant classes in the low concern risk-tier had comparable, though marginally less variable, overall removal rates than contaminants in the moderate concern risk-tier. Contaminant classes in the high

concern risk-tier (PFAS, OPEs) had fewer studies, more variability (Table A4), and worse removal rates compared to other classes. Contaminants in the possible concern category (tire- and vehicle-derived contaminants, other plastic additives) also had worse removal rates than those in the moderate and low concern tier, and had less data.

Table 5. Model-adjusted estimated marginal means removal rates $\pm$ Standard Error (SE) across contaminant classes. Chemical classes with the same pairwise grouping letter are not statistically different.

Chemical Class	RMP CEC Risk-Tier	Estimated Mean Removal (% $\pm$ SE)	95% Confidence Interval	Pairwise Grouping
OPE	High	16% $\pm$ 14%	[-23%, 56%]	a
PFAS	High	56% $\pm$ 13%	[19%, 92%]	ab
Bisphenols	Moderate	66% $\pm$ 11%	[35%, 98%]	ab
Microplastics	Moderate	89% $\pm$ 22%	[25%, 100%]	ab
Ethoxylated Surfactants	Low	61% $\pm$ 10%	[32%, 90%]	ab
Pharmaceuticals	Low	65% $\pm$ 5.6%	[47%, 82%]	b
Antibiotics	Low	65% $\pm$ 6.0%	[47%, 83%]	b
Personal Care Products	Low	74% $\pm$ 8.0%	[50%, 98%]	b
Tire- and Vehicle Derived	Possible	36% $\pm$ 11%	[4%, 68%]	ab
Other Plastic Additives	Possible	55% $\pm$ 11%	[24%, 86%]	ab
4-Methylphenol	Possible	Not Estimated	Not Estimated	Not Estimated

5. Conclusion

Overall, upgrading to advanced nutrient treatment trains can help remove CECs, although the effectiveness varies by contaminant class. Under the RMP's risk-based tiered framework, low-concern CECs have more data and consistently show higher removal rates across treatment technologies. In contrast, high- and possible-concern CECs remain insufficiently studied, underscoring the need for further investigation to properly characterize their removal across different treatment configurations. For instance, our search identified only two separate studies comparing the effectiveness of different treatment methods (outside of tertiary treatments) for PFAS and OPEs. A review of PFAS in WWTPs (Lenka et al., 2021) found that the majority of studies reported higher PFAS concentrations in effluent than in influent, suggesting that biodegradation transforms unknown precursors into terminal PFAS. These findings suggest a need to employ mixed analytical approaches, combining broader PFAS measurement methods with individual analyte quantification. The review also identified that tertiary treatment methods (e.g., electrochemical degradation, adsorption onto biochar, nanofiltration, etc.) are the most studied PFAS treatments. While there are numerous studies quantifying PFAS removal using tertiary treatment (Cagnetta et al., 2024; Jafarinejad, 2025; Talabazar et al., 2024 and others), there is a need to further conduct monitoring of PFAS, similar to Choi et al. (2022). Comparatively, OPEs exhibit lower removal across methods compared to PFAS, and may require similar additional treatments to achieve meaningful reductions. Furthermore, standardizing analytical techniques across studies and CECs classes would significantly facilitate direct data comparison.

Outcomes from this systematic review offer valuable guidance for designing future investigations of treatment technology performance. Key priorities include evaluating a broader spectrum of CECs not typically monitored (such as OPEs and PFAS) both prior to and following treatment upgrades. Additionally, assessing performance relative to influent concentration can assist in creating treatment performance curves (evaluating removal efficiency as a function of concentration), rather than relying solely on expected mean performance values for a particular treatment upgrade. Expanding the use of bioassays, moving beyond frequently selected endpoints like estrogenic and androgenic activity, could also be valuable for determining how effectively upgraded processes mitigate potential biological responses. Ultimately, such targeted investigations will help address crucial monitoring gaps surrounding CEC removal before and after facility upgrades.

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Appendices

Table A1. List of studies included in this review.

Reference	Scale	Treatment Technologies	SRT (days)	Sampling Method	Sampling Frequency	Sample Matrices	Analytical Methods
Bayo et al., 2020	Full-scale	MBR, RSF	7.75 - 9.75	Grab samples (~3 - 10 L)	53 grab samples between Feb 2018 and July 2019	Influent, MBR, tertiary treatment after RSF	Microscopic and spectroscopic identification
Bertanza et al., 2022	Full-scale	CAS, MBR	> 10	24-h flow-proportional composite sampling with hourly sub-samples	Daily for a two-week campaign	Influent, CAS effluent, MBR effluent	Chemical analyses, in vitro/in vivo bioassays (e.g., D. magna, YES, Ames, Comet)
Cases et al., 2011	Full-scale and pilot-scale	CAS with tertiary treatment (CAS-TT), Flat-sheet MBR (MBR-FS), Hollow-fibre MBR (MBR-HF)	NR	Grab sampling (10 mL extracted)	Weekly for 4 months (Oct 2009 - Jan 2010)	Primary settling tank effluent, CAS-TT effluent, MBR effluents	SBSE extraction with in situ derivatization, GC-MS
Chen et al., 2024	Full-scale	Modified Ludzack-Ettinger (MLE) with secondary settling (SST), MBR	NR	Grab sampling (1, 5, 60 L volumes)	Monthly for 12 months	Influent, primary/secondary settling effluents, MBR permeate, wet well	Ultrafiltration, DNA extraction, spectrophotometry
Choi et al., 2022	Full-scale and lab-scale	A2O-MBR, PAC adsorption, biofiltration (BAC), coagulation, MIEEX	NR	One-time grab sampling (1 L)	One-time	Influent, primary effluent, anaerobic/anoxic/aerobic zones, MBR, secondary effluent, UV, final effluent	SPE, LC-MS/MS, GC-MS/MS

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Reference	Scale	Treatment Technologies	SRT (days)	Sampling Method	Sampling Frequency	Sample Matrices	Analytical Methods
Coleman et al., 2009	Full-scale and pilot-scale	CAS, MBR	20	Grab sampling (7.5 L collected; 1 L aqueous or 0.5 g solid extracted)	One-time	Raw sewage (influent), MBR mixed liquor (biomass/aqueous), MBR effluent	SPE, yeast screen bioassays, GC-MS
De La Torre et al., 2015	Full-scale and pilot-scale	CAS, MBR, IFAS-MBR, MBMBR, RO	CAS; 10 MBR; 10 - 20	24-h composite sampling (4 h intervals)	Daily	Influent, permeate/effluent	SPE, HPLC-MS, HPLC with diode array/fluorescence detection
Dolar et al., 2012	Pilot-scale	MBR-RO integrated system	MBR; 45	Grab sampling (1 L)	5 occasions along one week	Raw municipal wastewater (influent), MBR effluent, RO permeate	Automated SPE, UPLC-QqLIT MS
Drewes et al., 2005	Full-scale and pilot-scale	CAS, nitrification-denitrification, MBR	CAS; 1.7 - 10, MBR; 10 - 21	4-h flow-proportional composite sampling (6 L)	Single sampling event per facility	Primary clarifier effluent, secondary clarifier effluent	HPLC-ELISA, GC-NCI-MS, E-screen bioassay
González-Pérez et al., 2017	Full-scale	MBR (pre-denitrification anoxic, aerobic, and membrane reactor)	37	24-h composite sampling (grabbed hourly, 1 L extracted from 5 L bottles)	Daily	Influent, effluent, purge, activated sludge	Physico-chemical analysis, instrumental micropollutant analysis
Gurung et al., 2017	Pilot-scale	Aerobic MBR system	25-30	24-h composite sampling (liquid) and grab sampling (sludge)	Weekly	Influent, permeate, mixed liquor (sludge)	SPE, LC-MS/MS, ICP-OES, Colilert/Enterolert enumerations
Itzel et al., 2018	Full-scale and pilot-scale	MBR, ozone, GAC, UV	NR	24-h composite sampling and random grab sampling (1 L)	Single sampling events	Influent, MBR effluent, after ozonation, after GAC, final effluent	SPE, LC-MS/MS, LC-Q/ToF-MS, HPLC fractionation, bioassays

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Reference	Scale	Treatment Technologies	SRT (days)	Sampling Method	Sampling Frequency	Sample Matrices	Analytical Methods
Kim et al., 2014	Full-scale	Hollow-fibre MBR	6-8	24-h equal volume composite sampling (400 mL every 30 mins) for liquid; grab sampling for solids	Three consecutive days	Influent, final effluent, biosolids	EPA Method 1694 (SPE, LC-MS/MS)
Lakshminarasimman et al., 2026	Full-scale	CAS, hybrid MABR/CAS	CAS; 5.4	24-h time proportional composite sampling (40 mL every 10 min into 10 L bottles); grab sampling for solids	3-year monitoring spanning warm and cold weather	Plant influent, MABR effluent, plant effluent, aeration tank MLSS, waste activated sludge	SPE, LC-MS/MS
Lares et al., 2018	Full-scale and pilot-scale	CAS, MBR	NR	Grab sampling with buckets/cups (4.0–30 L for water; 150–200 mL for sludge)	Every two weeks for 3 months	Influent, primary clarifier effluent, disinfected effluent, MBR permeate, lake water, sludges	Sieving (0.25 and 5.0 mm), optical microscopic examination
Le-Minh et al., 2010	Full-scale and pilot-scale	CAS, MBR, UV	CAS; 20-25 MBR; 40	Grab sampling (3-4 L)	Three separate periods plus a 24-h diurnal period (every 2 h)	Raw influent, MBR effluent, CAS secondary effluent, CAS-UV effluent	SPE, LC-MS/MS with isotope dilution
Le et al., 2018	Full-scale	CAS (MLE process), MBR	NR	Grab sampling (0.5 L for influent, 1.0 L for MLE effluents, 2.0 L for final effluents)	Not specified	Raw influent, MLE mixed liquor, secondary effluent, MBR permeate	DNA extraction, spectrophotometry, HPLC-MS/MS

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Reference	Scale	Treatment Technologies	SRT (days)	Sampling Method	Sampling Frequency	Sample Matrices	Analytical Methods
Lopez-Herguedas et al., 2024	Full-scale	CAS, MBR	NR	Composite sampling	Not specified	Primary effluent, CAS effluent, MBR effluent	LC-HRMS (suspect screening), GC-MS, Microtox® bioassay
Lubliner, 2008	Full-scale	CAS, advanced nutrient-removal, tertiary filtration, RO	CAS; 2.5 - 13 CBNR; 18.6 - 25	Hand-composited grab sampling (morning/noon/afternoon)	One-day screening	Influent, secondary effluent, tertiary effluent, biosolids	EPA Method 1694 (HPLC/MS/MS), EPA Method 1698 (HRGC/HRMS), EPA SW-846 8270d (GC/MS)
Lv et al., 2019	Full-scale	Oxidation ditch, A/A/O-MBR, UV disinfection	CAS 10 - 12; MBR 20.5	MP trapper via gravity (1–200 L)	One-time	Influent, mixed liquors, excess sludge, effluents	Sieving, microplastics characterization
Parker et al., 2014	Pilot-scale	CAS, CAS-N, BNR	CAS; 3 - 6 CBNR; 10 - 40	24-h composite sampling (1000 L specifically for fish tests)	Every 2 weeks for 6 months (Phase 1); weekly for 2 months (Phase 2)	Primary clarifier effluent, pilot effluents (CAS, CAS-N, BNR)	Chemical analyses, YES, YAS, T4/hTTR, zebrafish and fathead minnow bioassays
Pileggi et al., 2011	Pilot-scale	CAS, CAS-N, CAS-BNR	CAS; 6 CBNR; 20	24-h composite sampling (implied)	Continuous over a 6-month period	Primary effluent, pilot effluents	Chemical analyses (VOCs/ABNs), bioassays (YES/YAS, whole organism toxicity tests)
Potvin et al., 2012	Full-scale and pilot-scale	CAS, MBR, MABR	CAS; 12, MBR; 24 - 29	Grab sampling (CAS/MBR); 48–72 h composite sampling (MABR) 1 L	Routinely monitored	Influent, CAS effluent, MBR mixed-liquor, MBR permeate, MABR influent/effluent	TOC/TN analysis, particle size distribution, TBBPA quantitation
Qian et al., 2021	Full-scale and lab-scale	Activated sludge bioreactor (ASBR), various WWTP processes	NR	Centrifugation, filtration, 5 mL MTBE extractions	40-day bio-treatment period	Wastewater, sludge	Centrifugation, solvent extraction, instrumental analysis

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Reference	Scale	Treatment Technologies	SRT (days)	Sampling Method	Sampling Frequency	Sample Matrices	Analytical Methods
Radjenović et al., 2009	Full-scale and pilot-scale	CAS, HF MBR, FS MBR	CAS; 10	Flow-proportional 24-h composite sampling (100-200 mL); 4 L grab sampling for sludge	Daily for 9 days (water); weekly for 7 weeks (sludge)	Primary effluent, CAS effluent, MBR effluents, primary and activated sludges	SPE, pressurized liquid extraction (PLE/ASE), LC-MS/MS
Ren et al., 2017	Full-scale and lab-scale	MBR	NR	Not specified	Not specified	Influent, effluent	Cytotoxicity SRB assay (HEK293 cells)
Schneider et al., 2020	Full-scale and pilot-scale	CAS, ozonation, GAC, biofiltration (BF), MBR	CAS; NR MBR; 55	24-h composite sampling (500 mL)	Multiple campaigns	Primary treatment, secondary treatment, post-treatment (O3, GAC, BF, MBR)	SPE, multiple in vitro (e.g., Ames, CALUX) and in vivo bioassays
Stephenson & Oppenheimer, 2007	Full-scale and pilot-scale	Pure O2 AS, MLE, MBR, Deep bed filtration, RO, UV/chlorine	CAS; 4 - 6, 0.5 - 1.5, CBNR; 20 - 30, 3 - 5, 7 - 20, 11 - 16 MBR; 14 - 15	24-h time-weighted composite sampling (400 mL/60 min totaling 9.6 L); 2 L extracted	Summer and winter months	Raw influent, primary, secondary, tertiary, and MBR effluents	SPE, GC-MS-SIM
Sui et al., 2011	Full-scale	CAS, MBR, BNR (A/A/O)	CAS; 5 CBNR; 13 - 17, MBR; 18 - 23	Grab sampling (500 mL for influents, 1000 mL for others)	Monthly for 1 year (Feb 2009 - Jan 2010)	Influent, secondary effluent, MBR mixed liquors	SPE, UPLC-MS/MS
Tambosi et al., 2010	Pilot-scale	MBR	15 - 30	Grab sampling (500 mL)	Daily for 4 weeks	MBR permeate	SPE, LC-(HR)MS
Trinh et al., 2012	Full-scale	MBR, UV	10 - 15	SPE extraction onsite	Not specified	Raw sewage, MBR permeate	SPE, LC-MS/MS, GC-MS/MS

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Reference	Scale	Treatment Technologies	SRT (days)	Sampling Method	Sampling Frequency	Sample Matrices	Analytical Methods
Väitalo et al., 2017	Full-scale and pilot-scale	Activated sludge, MBBR, MBR, sand filtration	CAS; 14 - 16 CBNR; 9 - 17.25, MBR; 14 - 40	24-h composite sampling (6-43 L extracted via large SPE)	Feb-Mar 2015	Influent, effluent, MBR effluent	Large volume SPE (LVSPE50), comprehensive battery of in vitro/in vivo bioassays
Y. Wang et al., 2018	Pilot-scale	MBR-RO/NF	40	Grab sampling (1 L)	Taken during a one-week period	Influent, MBR effluent, RO/NF permeate	Filtration, instrumental analysis
S. Wang et al., 2020	Full-scale	MBR	NR	Centrifugation, 0.22 µm filtration	Not specified	MBR biomass/sludge, aqueous samples	DNA extraction, spectrophotometry

Table A2. Categorization of nitrogen-treatment technologies into broader groups identified in this study.

Original Treatment Technology	New Treatment Category
A/A/O Tank	Conventional Biological Nutrient Removal
A2/O + OD	Conventional Biological Nutrient Removal
Activated sludge + Denitrifying filters	Conventional Biological Nutrient Removal
Activated sludge + Sand filtration	Conventional Biological Nutrient Removal
AS+N	Conventional Biological Nutrient Removal
BAF	Conventional Biological Nutrient Removal
BNR	Conventional Biological Nutrient Removal
CA+F	Conventional Biological Nutrient Removal
CAS-BNR	Conventional Biological Nutrient Removal
CAS-N	Conventional Biological Nutrient Removal
CAS-TT	Conventional Biological Nutrient Removal
EBNR	Conventional Biological Nutrient Removal
EBNR+F	Conventional Biological Nutrient Removal
EBNR+MF	Conventional Biological Nutrient Removal
Ext. aeration	Conventional Biological Nutrient Removal
MLE	Conventional Biological Nutrient Removal
MUCT	Conventional Biological Nutrient Removal
Nit./Denit.	Conventional Biological Nutrient Removal
Activated sludge	Conventional Activated Sludge
Aeration Ditch	Conventional Activated Sludge
Conventional Activated Sludge	Conventional Activated Sludge

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Original Treatment Technology	New Treatment Category
High-purity O ₂ -activated sludge	Conventional Activated Sludge
Oxidation Ditch	Conventional Activated Sludge
A ₂ O-MBR	Membrane Bioreactor
AnOMBR-MD	Membrane Bioreactor
IFAS-MBR	Membrane Bioreactor
MBBR + activated sludge + Sand filtration	Membrane Bioreactor
MBBR + flotation	Membrane Bioreactor
MBMBR	Membrane Bioreactor
MBR	Membrane Bioreactor
MBR-FS	Membrane Bioreactor
MBR-HF	Membrane Bioreactor
MBR-NF	Membrane Bioreactor
MBR-RO	Membrane Bioreactor
MBR+O ₃	Membrane Bioreactor
SST+MBR	Membrane Bioreactor

Table A3. Type II Chi-Square test results for Linear Mixed Effects Model.

Fixed Effect Factor	Chi-Square (χ^2)	Degrees of freedom	p-value
Treatment	5.0868	2	0.0785
CEC Class	32.1576	9	<0.0001
Treatment x CEC Class	39.1382	17	0.0017

Table A4. Model-adjusted estimated marginal means across treatment categories. Treatments with the same pairwise grouping letter are not statistically different.

Treatment	Number of Studies	Total Data Points	Estimated Mean Removal (% $\pm$ SE)	95% Confidence Interval	Pairwise Grouping
CS	14	225	57.0% $\pm$ 5.9%	[45.0%, 68.9%]	a
CBNR	6	158	60.9% $\pm$ 7.2%	[46.4%, 75.3%]	a
MBR	23	534	67.1% $\pm$ 5.0%	[56.8%, 77.4%]	a

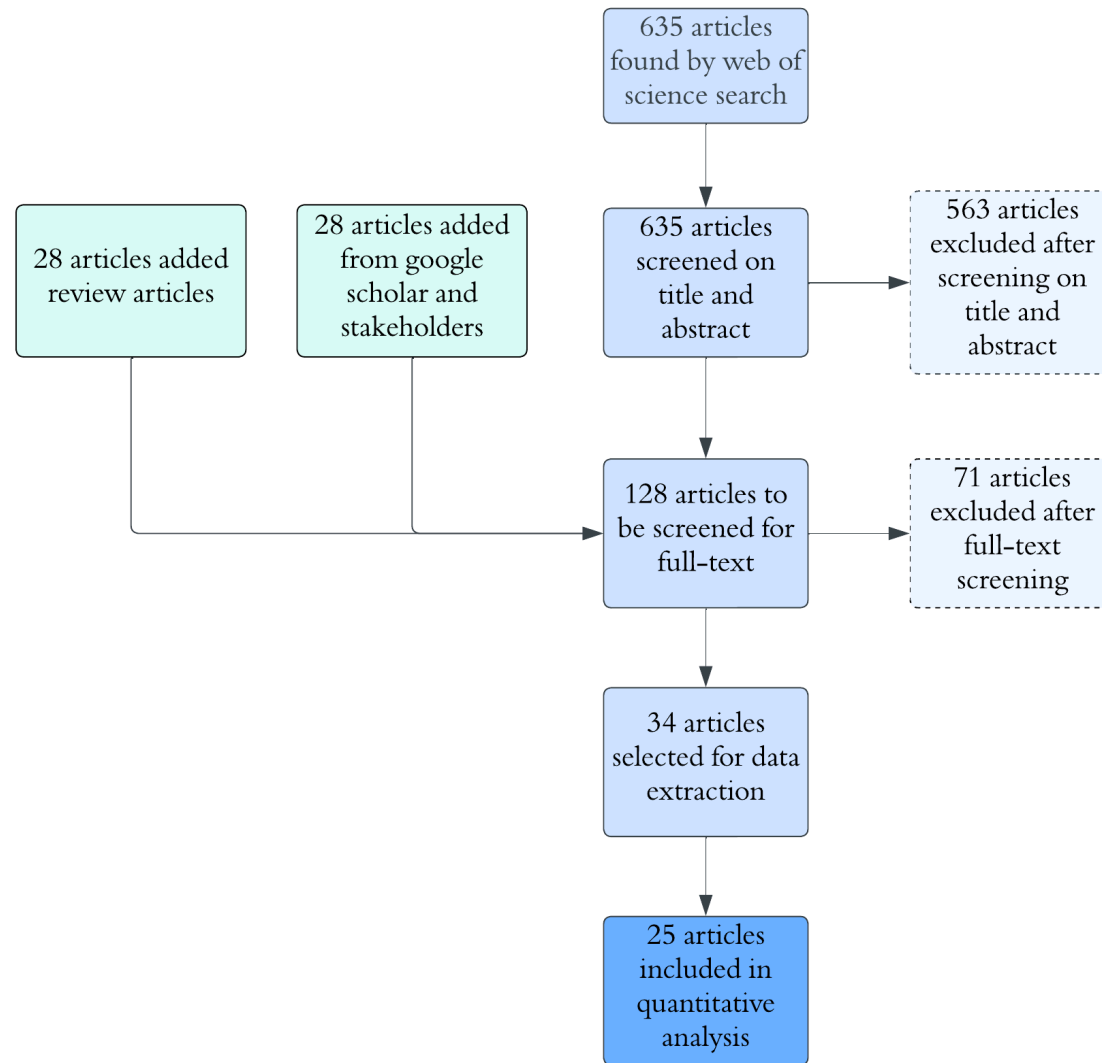


Figure A1. Flow diagram of studies included in this review

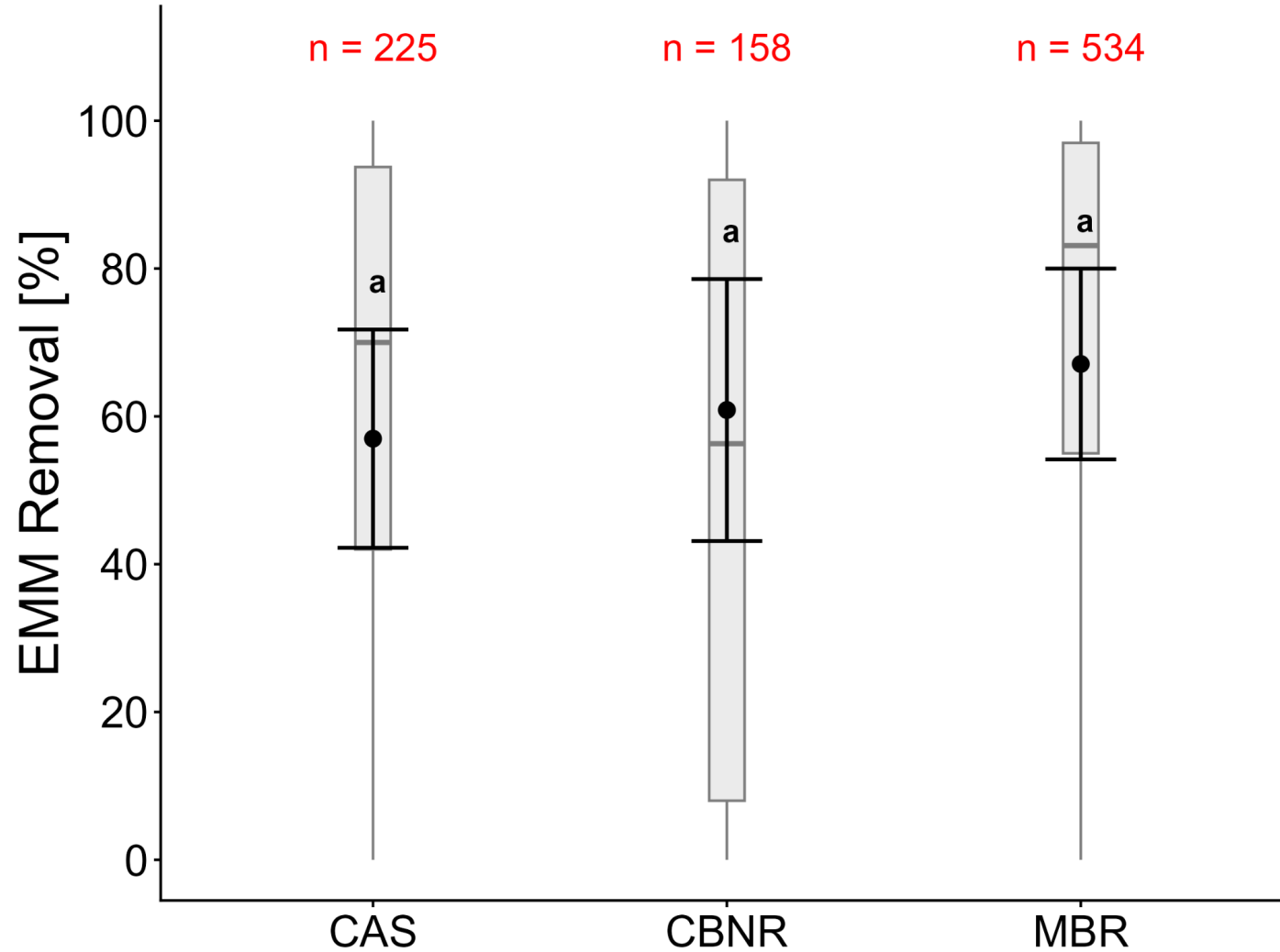


Figure A2. Estimated Marginal Mean (EMM) Removal for each broader treatment category. Error bars are standard error. Boxplots represent the raw data. The red n = indicates the number of data points. Treatments with the same pairwise grouping letter are not statistically different.

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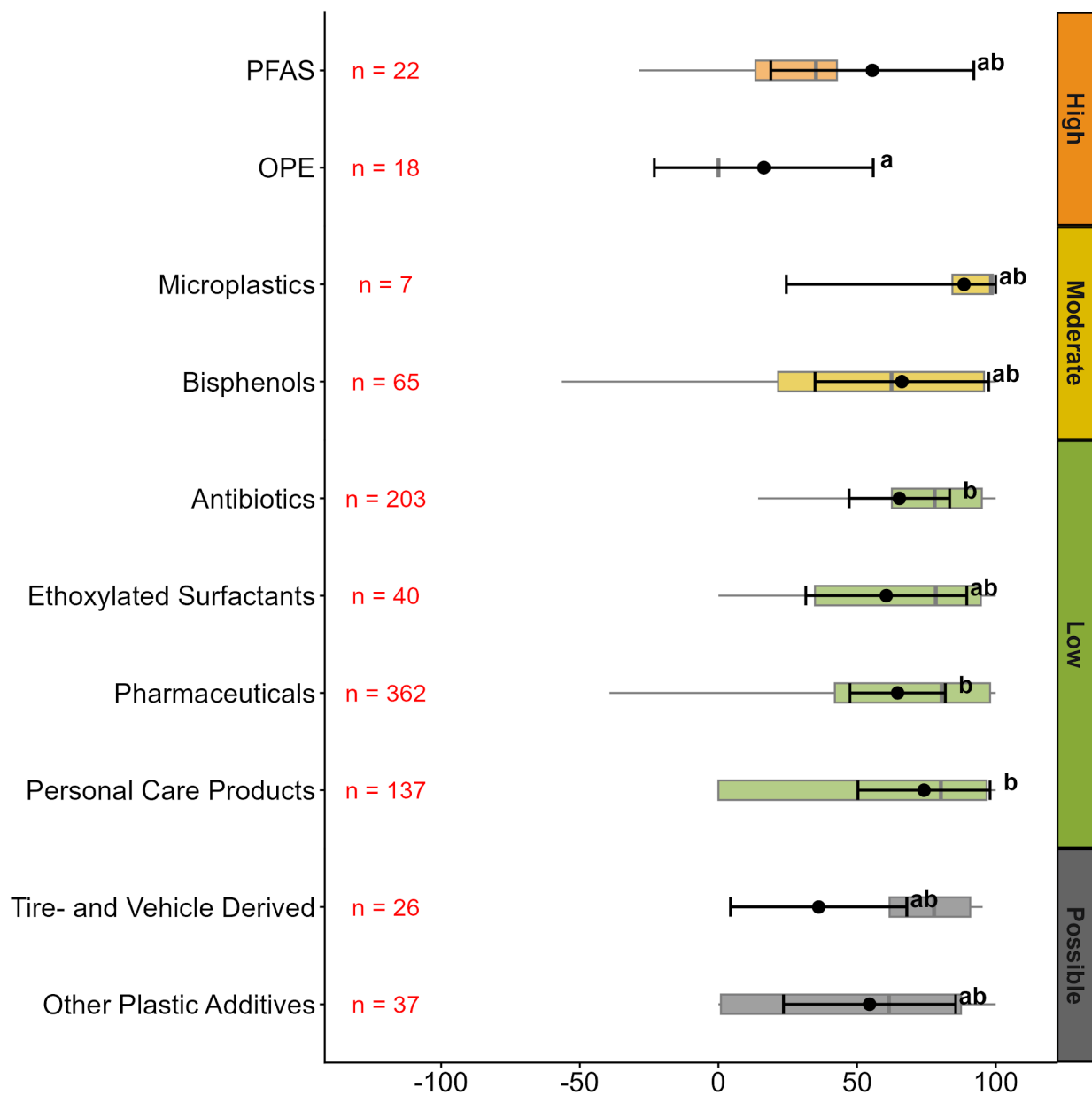


Figure A3. Estimated Marginal Mean (EMM) Removal for each contaminant class. Boxplots represent the raw data. Error bars are standard error. The red n = indicates the number of data points. Treatments with the same pairwise grouping letter are not statistically different.

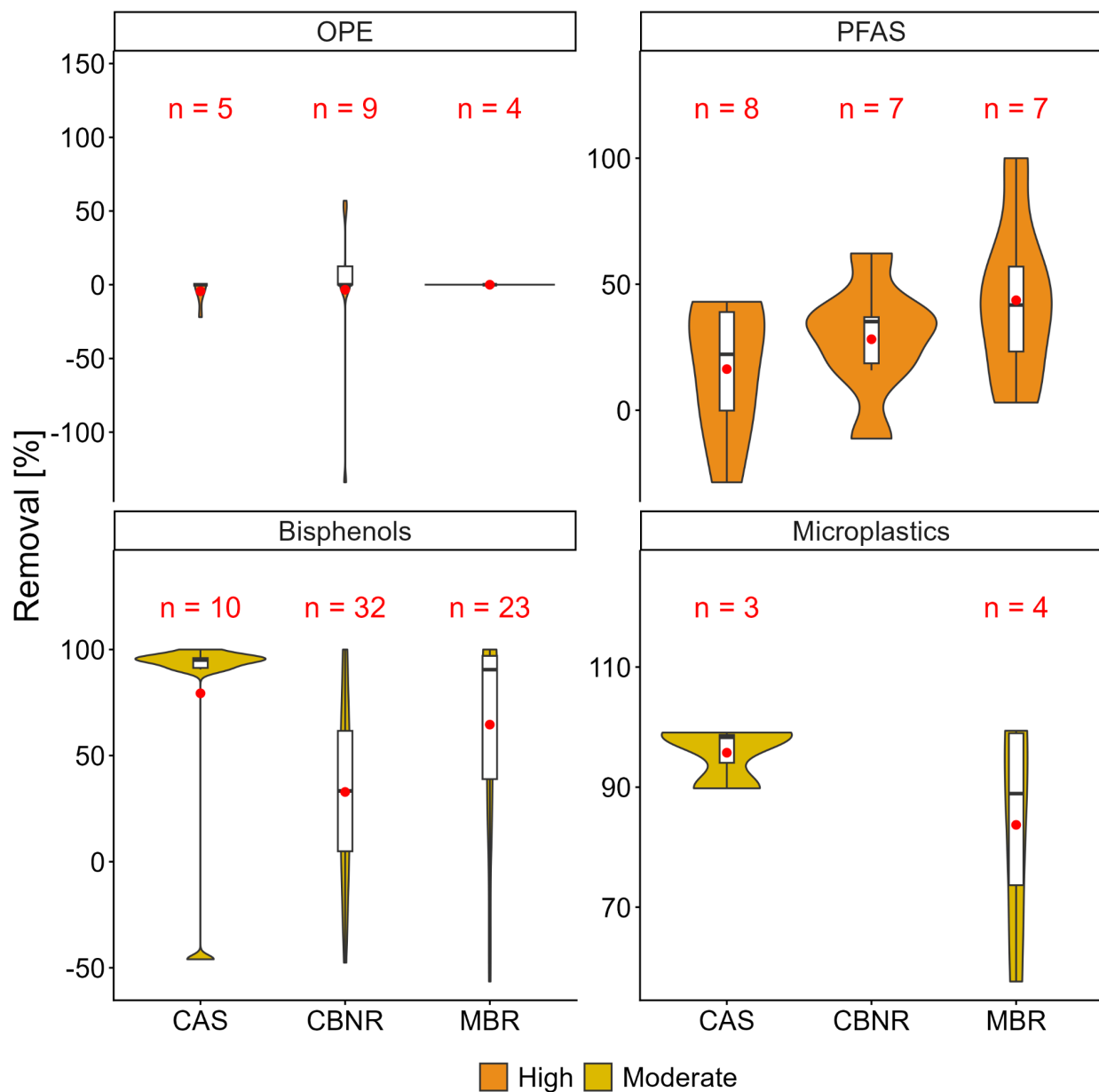


Figure A4. Violin plots of removal [%] for each broader treatment category for contaminant classes in the high and moderate risk tier. Wider sections indicate higher data density, while narrower sections indicate fewer data points. The red dot is the arithmetic mean for that category. The red n = indicates the number of data points

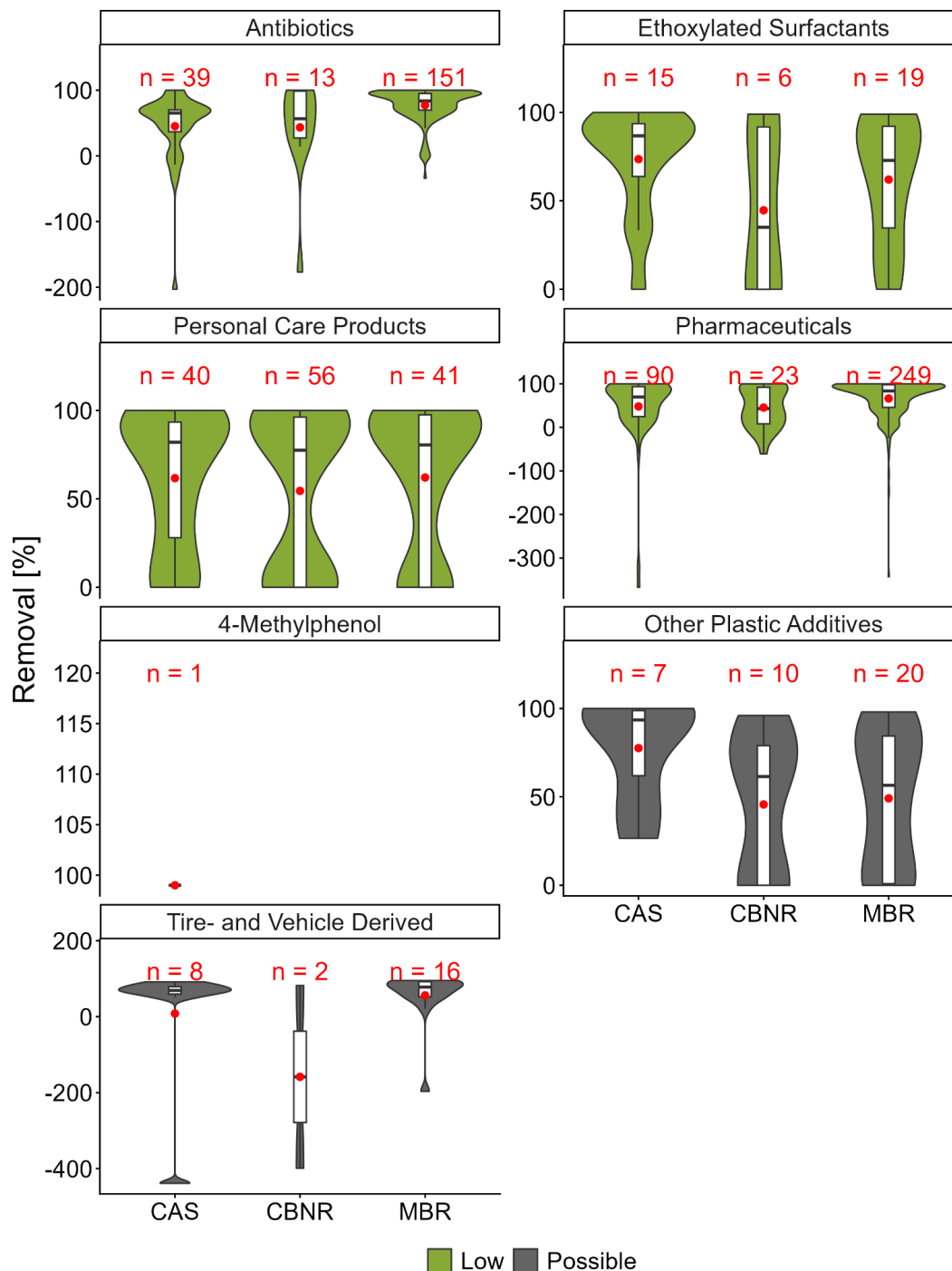


Figure A5. Violin plots of removal [%] for each broader treatment category for contaminant classes in the low and possible risk tier. Wider sections indicate higher data density, while narrower sections indicate fewer data points. The red dot is the arithmetic mean for that category. The red n = indicates the number of data points