PFAS Treatment Evaluation via Bench-Scale Rapid Small-Scale Column Testing with CAST Pretreatment

Christopher M. Fetters, P.E., June 2025, Technical Paper Flotration Technologies.

Introduction to PFAS Treatment Technologies

The widespread presence of per- and polyfluoroalkyl substances in the environment has led to the development and implementation of various treatment technologies aimed at their removal and destruction (Jahnke & Berger, 2008). Due to their resistance to natural degradation processes and their ability to persist in humans, animals, and environmental matrices, PFAS have attracted increasing attention (Nahar et al., 2023; Panieri et al., 2022). Their extensive use in numerous industrial and consumer applications has resulted in their pervasive presence in aquatic environments, highlighting the need for effective treatment strategies (Kurwadkar et al., 2021). Therefore, mitigation strategies are essential for addressing PFAS contamination (Lukić-Bilela et al., 2023). Innovative analytical methods have been developed for detecting ionic and neutral PFAS in various matrices, assisting in their identification and quantification within complex environmental samples (Jahnke & Berger, 2008). However, determining PFAS at trace concentrations in complex matrices remains a significant analytical challenge, emphasizing the need for simplified and reliable methods for routine environmental monitoring, food safety, and biological sample analysis (Trojanowicz & Koc, 2013). These advanced analytical techniques are vital for evaluating the effectiveness of treatment technologies and ensuring regulatory compliance (Caniglia et al., 2022; Jahnke & Berger, 2008). Furthermore, the discovery of PFAS ubiquity in wildlife, humans, and the global environment less than a decade ago has prompted the demand for robust, reliable, and highly sensitive analytical methods for their determination in various matrices (Jahnke & Berger, 2008).

Rapid Small-Scale Column Tests are often employed to simulate the performance of full-scale treatment processes in a laboratory setting, providing a cost-effective and time-efficient means of evaluating different treatment options. The bench-scale test report focuses on a rapid, small-scale column testing methodology, which is crucial in assessing the effectiveness of treatment technologies like CAST pretreatment for PFAS removal. This technology offers a promising avenue for addressing PFAS contamination in water sources and underscores the importance of ongoing research and development efforts in this field. The increasing number of research papers on perfluoroalkyl substances in recent years demonstrates the growing scientific interest and concern surrounding these compounds (Trojanowicz & Koc, 2013). Integrating pretreatment processes like Flotation Technologies' CAST system prior to GAC adsorption represents a promising strategy for enhancing the overall efficiency and longevity of PFAS removal. Moreover, electrochemical methods are being explored to determine the mechanisms of PFAS removal in detail. This pretreatment aims to improve the performance of subsequent treatment processes, such as ion exchange, by removing organic matter and other contaminants that can interfere with PFAS removal. The method offers a streamlined approach to mimic full-scale media vessel designs, enabling a practical assessment of treatment effectiveness within a compressed timeframe. The bench-scale test report assessing the efficacy of the CAST pretreatment in conjunction with RSSCT for PFAS treatment holds significant importance for optimizing treatment strategies and informing decision-making processes in water treatment facilities.

Technical Review of Bench-Scale Test Report

A comprehensive technical review of the bench-scale test report is essential for evaluating the experimental design, data analysis, and conclusions regarding the effectiveness of CAST pretreatment in enhancing PFAS removal during RSSCT. The experimental design in the bench test report involved a comparative analysis of influent PFAS concentrations in two distinct test scenarios: one using CAST pretreatment and another without it. Like the testing performed on air suction flow-biofilm reactors, bench-scale testing allows for controlled experimentation and optimization of treatment processes (Forde et al., 2014). Careful consideration should be given to potential scale effects, as the performance observed in bench-scale tests may not directly translate to full-scale applications due to differences in hydrodynamics, flow patterns, and other operational parameters. The thorough documentation of the experimental setup, procedures, and results enhances the reliability and transparency of the study. The evaluation of the test report should include several critical aspects, encompassing a detailed examination of the materials and methods employed, scrutiny of the quality control measures implemented, and a comprehensive assessment of the data analysis techniques used.

The bench test results demonstrated that CAST pretreatment significantly influenced the performance of ion exchange resins in removing PFAS from contaminated water. Specifically, perfluoroalkyl ether carboxylic acids such as DA, NFDHA, PFMOBA, and PFMOPrA exhibited minimal breakthrough throughout the loading experiment, with both treatment scenarios achieving over 99.9% removal. Additional data analysis and interpretation are required to assess the statistical significance of the observed differences and establish the robustness of the findings. Analyzing water quality parameters can provide a baseline against which the effectiveness of treatment processes can be evaluated and compared (Wallace et al., 2014). Moreover, the test report should thoroughly evaluate the data quality, addressing any potential sources of error or uncertainty in the measurements. A comprehensive analysis of the data presented in Figures A.3 to A.13, as highlighted in the bench test report, offers valuable insights into the effectiveness of CAST pretreatment in enhancing the removal of various PFAS compounds using DOWEX PSR2+ resin.

The findings from this report align with broader efforts to develop and optimize effective PFAS treatment strategies for safeguarding water resources and public health. This collaborative approach facilitates the exchange of knowledge, expertise, and resources, accelerating the development and implementation of innovative solutions for addressing PFAS contamination on a global scale. By selectively removing certain organic constituents, CAST pretreatment reduces competition for binding sites on the ion exchange resin, allowing for more efficient PFAS removal. The CAST pretreatment system employed in the experiment likely induced changes in DOC composition by selectively removing specific organic matter fractions. This study provides critical data for optimizing the design and operation of full-scale PFAS treatment systems.

The bench-scale test report offers valuable insights into the effectiveness of CAST pretreatment combined with DOWEX PSR2+ resin for PFAS removal, providing a foundation for further research and development in this critical area. It would be interesting to compare and contrast CAST pretreatment with alternative methods like magnetic anion exchange resin, which has been shown to effectively remove dissolved organic carbon and color from dyeing secondary effluent (Yang et al., 2014). Further research could explore the application of modified biochar for the simultaneous adsorption of organic pollutants and heavy metal ions, offering a comprehensive solution for water treatment. Future studies should evaluate the long-term performance and cost-effectiveness of integrated treatment systems incorporating CAST pretreatment and ion exchange for PFAS removal. It is also essential to develop analytical methods that are both reliable and cost-effective for monitoring PFAS in various environmental matrices.

Experimental Design and Methodology

Bench-scale testing that utilizes rapid small-scale column testing is a cost-effective and time-efficient way to assess the performance of various treatment technologies for PFAS removal. In a recent study, Flotration Technologies contracted ECT2 to conduct this evaluation, focusing on PFAS treatment with and without preliminary treatment using Flotration's proprietary CAST treatment technology. The experimental design featured a comparative analysis of influent PFAS concentrations in two distinct test scenarios: one employing the CAST pretreatment and the other operating without it. Influent concentrations between the two tests were comparable, with the percentage differences for individual PFAS compounds falling within the margin of error of the analytical methods used. The rapid small-scale column testing methodology used in this study simulates the performance of full-scale treatment systems, offering valuable insights into the efficacy of PFAS removal under controlled conditions. Dow's PSR2+ ion exchange resin was used for PFAS treatment alongside Flotration. CAST technology is not detailed in this bench test report. Flotration Technologies contracted ECT2 to evaluate PFAS treatment in test water with and without preliminary treatment using Flotration's CAST treatment technology. The project site associated with this test water is expected to require treatment of 20 gpm of flow, with treatment targets aligned with USEPA MCLs for PFAS, which are 4 ng/L for PFOA and PFOS, 10 ng/L for PFHxS, PFNA, and HFPO-DA, and a Hazard Index of 1.

The bench-scale test report provides critical data on the performance of the CAST pretreatment in enhancing PFAS removal during RSSCT, and the findings suggest that the CAST pretreatment can significantly improve the performance of subsequent PFAS treatment processes. A thorough review of the experimental design, analytical methods, and data interpretation is necessary to fully evaluate the CAST pretreatment's effectiveness. The findings revealed that PFOA broke through above the 4 ng/L mark first in the CAST-treated water between 8,394 and 14,722 bed volumes, corresponding to 13,276 bed volumes treated. PFOA first broke through above the 4 ng/L mark in the non-CAST-treated water between 2,580 and 8,394 bed volumes, corresponding to 5,487 bed volumes treated. PFOS broke through above the 4 ng/L threshold at approximately 13,767 bed volumes in the CAST-treated water, whereas in the non-CAST-treated water, this threshold was exceeded at fewer than

1,619 bed volumes. The integration of CAST pretreatment resulted in about 34,000 bed volumes for the CAST-treated water. In comparison, the non-CAST-treated water hit this mark at approximately 8,000 bed volumes, highlighting the enhanced bed volume processing before the PFAS concentration reaches the MCLs. Analyzing the data will help determine the mechanisms of PFAS removal in the presence of the CAST pretreatment and provide insights into its potential application for full-scale PFAS remediation.

Results and Discussion

The results of the bench-scale testing revealed that the combination of CAST pretreatment and ion exchange using Dow's PSR2+ resin demonstrated superior performance in removing PFAS compared to ion exchange alone. The data indicated a notable difference in the breakthrough curves for several PFAS compounds, with the CAST pretreatment group exhibiting delayed breakthrough and extended column capacity. Breakthrough curves plotting concentration against bed volumes treated illustrated the removal efficiencies of various PFAS compounds using both treatment scenarios.

Notably, the study examined the impact of CAST pretreatment on removing specific PFAS compounds, including PFOA, PFNA, PFBS, 8:2 FTS, PFOSA, and 5:3 FTCA. The figures presented in the report visually demonstrate the improved performance achieved with the integrated CAST pretreatment and ion exchange process. By selectively removing certain organic constituents, CAST pretreatment may reduce competition for binding sites on the ion exchange resin, allowing for more efficient PFAS removal. The study highlights the potential of combining complementary treatment processes to achieve synergistic effects in PFAS removal, as hybrid treatment processes lead to improved effectiveness stemming from the synergistic interactions between processes with distinct removal mechanisms (Loganathan et al., 2024). Ion exchange processes represent an efficient technology for the remediation of PFAS-laden surface, ground, and effluent wastewaters, proving more effective at eliminating emerging short-chain PFAS, which are not removed by carbon-based adsorption processes (Dixit et al., 2021). The characteristics of organic matter are spatially variable and can change seasonally, and this variability can affect the efficacy of PFAS removal by ion exchange (Dixit et al., 2019).

Specifically, perfluoroalkyl ether carboxylic acids such as DA, NFDHA, PFMOBA, and PFMOPrA exhibited minimal breakthrough throughout the loading experiment, with both treatment scenarios achieving over 99.9% removal (Fang et al., 2022). This observation suggests that the ion exchange resin used in the study has a strong affinity for these specific PFAS compounds, regardless of CAST pretreatment.

The bench test report details a specific instance where PFOS broke through above the 4 ng/L threshold at approximately 13,767 bed volumes in the CAST-treated water, whereas, in the non-CAST-treated water, this threshold was exceeded at fewer than 1,619 bed volumes. The C/Co ratio reached 20% at about 34,000 bed volumes for the CAST-treated water, while the non-CAST-treated water hit this mark at approximately 8,000 bed volumes. This difference highlights the enhanced capacity and delayed breakthrough achieved by integrating CAST pretreatment. This data reinforces the concept that strategic pretreatment can substantially improve the longevity and efficiency of downstream treatment processes.

Data Interpretation and Analysis

The bench-scale test report provides valuable data and insights into the performance of CAST pretreatment combined with ion exchange for PFAS removal. However, the data presented in the report contains inherent limitations related to bench-scale testing, such as scale effects, simplified water matrices, and controlled operational conditions. When interpreting the data, it is vital to consider these limitations and carefully extrapolate the findings to real-world scenarios. Specifically, the observed improvement in PFAS removal with CAST pretreatment may be attributed to several factors, including eliminating competing organic matter, reducing fouling potential, and modifying PFAS speciation (Dixit et al., 2020). Although granular activated carbon adsorption has been extensively studied for PFAS removal, alternative adsorbents and the effects of pretreatment processes on their performance have received less attention (Pannu et al., 2023). Further research is required to elucidate the underlying mechanisms and optimize the integration of CAST pretreatment with ion exchange for various water matrices and PFAS mixtures.

Despite extensive studies on PFAS degradation, significant gaps in experimental data impede complete efficiency evaluations, underscoring the need for cost-effective and safe mineralization technologies (Meegoda et al., 2022). Addressing PFAS pollution in water is a top priority for public health and environmental protection organizations because of the serious health hazards of PFAS exposure (Amen et al., 2023). Given the prevalence and persistence of PFAS in the environment, water treatment technologies must evolve to eliminate these substances and safeguard water resources effectively. Conventional treatment technologies often struggle to remove PFAS effectively, particularly when other contaminants are present (Loganathan et al., 2024).

In conclusion, the bench-scale test report comprehensively evaluates CAST pretreatment's performance in enhancing PFAS removal through ion exchange. The results demonstrate that CAST pretreatment can substantially improve the efficiency and longevity of ion exchange resins for PFAS removal, offering a promising strategy for tackling PFAS contamination in water. The Flotration Technologies project site associated with this test water is expected to require treatment of 20 gpm of flow, with treatment targets assumed to be the USEPA MCLs for PFAS to establish a basis for comparison between tests. The experimental design involved a comparative analysis of influent PFAS concentrations in two distinct test scenarios: one employing the CAST pretreatment and another lacking it. The enhanced performance observed with CAST pretreatment underscores the importance of strategic process design and optimization in achieving effective and sustainable PFAS removal. The hydrophobic and electrostatic interactions serve as the primary mechanisms for eliminating PFAS (Amen et al., 2023; Dixit et al., 2021). The differences in performance between the two scenarios highlight the complex interplay of factors influencing PFAS removal and the potential benefits of integrating complementary treatment processes. Ultimately, the effective mitigation of PFAS contamination necessitates a comprehensive strategy integrating source control measures, advanced treatment technologies, and responsible management practices.

Conclusion

The bench-scale test report thoroughly evaluates the performance of CAST pretreatment in enhancing PFAS removal through ion exchange. The data presented in the report support the conclusion that CAST pretreatment can significantly improve the efficiency and capacity of ion exchange resins for PFAS removal.

Bench-scale testing offers insights into the performance of the combined treatment approach under controlled conditions. Additional research is necessary to validate these findings in pilot-scale and full-scale studies and optimize the design and operation of integrated treatment systems incorporating CAST pretreatment and ion exchange for PFAS removal. However, these separation technologies do not destroy PFAS compounds; they remain in the environment, posing health risks (Meegoda et al., 2022). Therefore, further research and development of destruction technologies for PFAS are essential. Solutions in detection, analysis, immobilization, destruction, and safer alternatives are urgently needed (Itumoh et al., 2024). Emerging technologies, such as plasma treatment, have shown promise in laboratory settings for PFAS degradation (Topolovec et al., 2024). The bench-scale study is an important step, but it is critical to acknowledge its limitations and the need for further research to validate and optimize the technology for real-world applications (Meegoda et al., 2022). Developing efficient strategies for identifying and quantifying emerging PFAS is essential for risk assessment (Nakayama et al., 2019). Rapidly expanding scientific understanding and creating effective strategies for legislative regulation, remediation, and therapeutic interventions to reduce potential effects on humans and biota is crucial (Panieri et al., 2022). Flotration continues to evaluate the CAST technology in concert with several technologies, including options for absorption and destruction. As the evaluation of GAC and resins continues, the destruction technology focuses on pyrolysis. However, the primary goal remains the removal of PFAS from the water supply through the best means available.

Rapid small-scale column testing is designed to simulate full-scale media vessel designs within a condensed timeframe, offering a practical means to assess treatment efficacy. Optimizing treatment processes for PFAS-contaminated media is essential for minimizing environmental impact and safeguarding public health (Xiao et al., 2023). These pilot studies must be carefully designed and implemented to accurately represent real-world conditions and provide reliable data for full-scale implementation.

References

Loganathan, P., Kandasamy, J., Ratnaweera, H., & Vigneswaran, S. (2024). Treatment Trends and Hybrid Methods for the Removal of Poly- and Perfluoroalkyl Substances from Water—A Review. Applied Sciences, 14(6), 2574. https://doi.org/10.3390/app14062574

Newman, B. 2025. Bench Test Report: Rapid Small-Scale Column Testing to Evaluate PFAS Treatment with CAST Pretreatment.

Abbey, C. Y. B., Duwiejuah, A. B., & Quianoo, A. K. (2022). Remove toxic metals from the aqueous phase using cacao pod husk biochar in the era of green chemistry. Applied Water Science, 13(2). https://doi.org/10.1007/s13201-022-01863-5

Abu-Nada, A., Abdala, A., & McKay, G. (2021). Removal of phenols and dyes from aqueous solutions using graphene and graphene composite adsorption: A review [Review of Removal of phenols and dyes from aqueous solutions using graphene and graphene composite adsorption: A review]. Journal of Environmental Chemical Engineering, 9(5), 105858. Elsevier BV. https://doi.org/10.1016/j.jece.2021.105858

Ahmed, M. A., Ahmed, M. A., & Mohamed, A. A. (2021). A facile and rapid removal of cationic dyes using hierarchically porous reduced graphene oxide decorated with manganese ferrite. FlatChem, 26, 100233. https://doi.org/10.1016/j.flatc.2021.100233

Ahmed, M., Mavukkandy, M. O., Giwa, A., Elektorowicz, M., Katsou, E., Khelifi, O., Naddeo, V., & Hasan, S. W. (2022). Recent developments in hazardous pollutants removal from wastewater and water reuse within a circular economy. Npj Clean Water, 5(1). https://doi.org/10.1038/s41545-022-00154-5

Alberoni, C., Barroso-Martín, I., Infantes-Molina, A., Rodríguez-Castellón, E., Talon, A., Zhao, H., You, S., Vomiero, A., & Moretti, E. (2021). Ceria doping boosts methylene blue photodegradation in titania nanostructures. Materials Chemistry Frontiers, 5(11), 4138. https://doi.org/10.1039/d1qm00068c

Amen, R., Ibrahim, A., Shafqat, W., & Hassan, E. B. (2023). A Critical Review on PFAS Removal from Water: Removal Mechanism and Future Challenges [Review of A Critical Review on PFAS Removal from Water: Removal Mechanism and Future Challenges]. Sustainability, 15(23), 16173. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/su152316173

Amin, M. T., Alazba, A. A., & Manzoor, U. (2014). A Review of Removal of Pollutants from Water/Wastewater Using Different Types of Nanomaterials [Review of A Review of Removal of Pollutants from Water/Wastewater Using Different Types of Nanomaterials]. Advances in Materials Science and Engineering, 2014, 1. Hindawi Publishing Corporation. https://doi.org/10.1155/2014/825910

Amini, A., Kim, Y., Zhang, J., Boyer, T. H., & Zhang, Q. (2015). Environmental and economic sustainability of ion exchange drinking water treatment for organics removal. Journal of Cleaner Production, 104, 413. https://doi.org/10.1016/j.jclepro.2015.05.056

Awaleh, M. O. (2014). Waste Water Treatment in Chemical Industries: The Concept and Current Technologies. Hydrology Current Research, 5(1). https://doi.org/10.4172/2157-7587.1000164

Boer, S. de, González-Rodríguez, J., Conde, J. J., & Moreira, M. T. (2022). Benchmarking tertiary water treatments to remove micropollutants and pathogens based on operational and sustainability criteria. Journal of Water Process Engineering, 46, 102587. https://doi.org/10.1016/j.jwpe.2022.102587

Borne, K. E., Fassman-Beck, E., & Tanner, C. C. (2013). Floating Treatment Wetland influences on the fate of metals in road runoff retention ponds. Water Research, 48, 430. https://doi.org/10.1016/j.watres.2013.09.056

Burkhardt, J. B., Burns, N., Mobley, D., Pressman, J. G., Magnuson, M. L., & Speth, T. F. (2021). Modeling PFAS Removal Using Granular Activated Carbon for Full-Scale System Design. Journal of Environmental Engineering, 148(3). https://doi.org/10.1061/(asce)ee.1943-7870.0001964

Caniglia, J., Snow, D. D., Messer, T., & Bartelt-Hunt, S. L. (2022). Extraction, analysis, and occurrence of per- and polyfluoroalkyl substances (PFAS) in wastewater and after municipal biosolids land application to determine agricultural loading. Frontiers in Water, 4. https://doi.org/10.3389/frwa.2022.892451

Cardoso, I. M. F., Silva, L. P. da, & Silva, J. C. G. E. da. (2023). Nanomaterial-Based Advanced Oxidation/Reduction Processes for the Degradation of PFAS [Review of Nanomaterial-Based Advanced Oxidation/Reduction Processes for the Degradation of PFAS]. Nanomaterials, 13(10), 1668. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/nano13101668

Chen, Z., Zhao, Y., Wei, T., & Shen, C. (2025). Leading Techniques for Per- and Polyfluoroalkyl Substances (PFASs) Remediating in Water and Wastewater. Water, 17(9), 1319. https://doi.org/10.3390/w17091319

Cooper, A. M., Torrens, K. D., & Musterman, J. L. (1992). On-site evaluation of treatment system requirements to satisfy direct and indirect discharge limits for a complex industrial wastewater: A case study. Environmental Progress, 11(1), 18. https://doi.org/10.1002/ep.670110113

Dixit, F., Barbeau, B., Mostafavi, S. G., & Mohseni, M. (2019). PFOA and PFOS removal by ion exchange for water reuse and drinking applications: role of organic matter characteristics. Environmental Science Water Research & Technology, 5(10), 1782. https://doi.org/10.1039/c9ew00409b

Dixit, F., Barbeau, B., Mostafavi, S. G., & Mohseni, M. (2020). Removal of legacy PFAS and other fluorotelomers: Optimized regeneration strategies in DOM-rich waters. Water Research, 183, 116098. https://doi.org/10.1016/j.watres.2020.116098

Dixit, F., Dutta, R., Barbeau, B., Bérubé, P. R., & Mohseni, M. (2021). PFAS removal by ion exchange resins: A review [Review of PFAS removal by ion exchange resins: A review]. Chemosphere, 272, 129777. Elsevier BV. https://doi.org/10.1016/j.chemosphere.2021.129777

Echevarría, C., Valderrama, C., Cortina, J. L., Martín, I. S., Arnaldos, M., Bernat, X., Cal, A. de la, Boleda, M. R., Benítez, A. N., Teuler, A., & Castellví, E. (2020). Hybrid sorption and pressure-driven membrane technologies for organic micropollutants removal in advanced water reclamation: A techno-economic assessment. Journal of Cleaner Production, 273, 123108. https://doi.org/10.1016/j.jclepro.2020.123108

Elena, A., Orbeci, C., Lăzău, C., Sfîrloagă, P., Vlăzan, P., Bandas, C., & Grozescu, I. (2013). Waste Water Treatment Methods. In InTech eBooks. https://doi.org/10.5772/53755

Evich, M. G., Davis, M. J. B., McCord, J., Acrey, B., Awkerman, J. A., Knappe, D. R. U., Lindstrom, A. B., Speth, T. F., Tebes-Stevens, C., Strynar, M. J., Wang, Z., Weber, E., Henderson, W. M., & Washington, J. W. (2022). Per- and polyfluoroalkyl substances in the environment [Review of Per- and polyfluoroalkyl substances in the environment]. Science, 375(6580). American Association for the Advancement of Science. https://doi.org/10.1126/science.abg9065

Fan, Q., Gong, T., Dong, Q., & Wang, W. (2023). Uncovering hydrothermal treatment of per- and polyfluoroalkyl substances. Eco-Environment & Health, 2(1), 21. https://doi.org/10.1016/j.eehl.2023.02.002

Fang, Y., Meng, P., Schaefer, C. E., & Knappe, D. R. U. (2022). Removal and destruction of perfluoroalkyl ether carboxylic acids (PFECAs) in an anion exchange resin and electrochemical oxidation treatment train. Water Research, 230, 119522. https://doi.org/10.1016/j.watres.2022.119522

Fuks, L., Miśkiewicz, A., & Zakrzewska-Kołtuniewicz, G. (2022). Sorption-Assisted Ultrafiltration Hybrid Method for Treatment of the Radioactive Aqueous Solutions. Chemistry, 4(3), 1076. https://doi.org/10.3390/chemistry4030073

Hanafi, M. F., & Sapawe, N. (2020). A review on the current techniques and technologies of organic pollutants removal from water/wastewater [Review of A review on the current techniques and technologies of organic pollutants removal from water/wastewater]. Materials Today Proceedings, 31. Elsevier BV. https://doi.org/10.1016/j.matpr.2021.01.265

Horst, J., McDonough, J. T., Ross, I. L., & Houtz, E. (2020). Understanding and Managing the Potential By-Products of PFAS Destruction. Groundwater Monitoring & Remediation, 40(2), 17. https://doi.org/10.1111/gwmr.12372

Itumoh, E. J., Data, S., Chen, J. L. -Y., Kah, M., Padhye, L. P., & Leitao, E. M. (2024). Addressing the Persistence of Per- and Polyfluoroalkyl Substances (PFAS): Current Challenges and Potential Solutions. RSC Sustainability, 2(11), 3183. https://doi.org/10.1039/d4su00152d

Jabłońska, B. (2018). Water consumption management in polyethylene terephthalate (PET) bottles washing process via wastewater pretreatment and reuse. Journal of Environmental Management, 224, 215. https://doi.org/10.1016/j.jenvman.2018.07.054

Jahnke, A., & Berger, U. (2008). Trace analysis of per- and polyfluorinated alkyl substances in various matrices—How do current methods perform? [Review of Trace analysis of per- and polyfluorinated alkyl substances in various matrices—How do current methods perform?]. Journal of Chromatography A, 1216(3), 410. Elsevier BV. https://doi.org/10.1016/j.chroma.2008.08.098

Kaur, H., Kumar, A., Koner, R. R., & Krishnan, V. 2020. Metal-organic frameworks for photocatalytic degradation of pollutants. In Elsevier eBooks (p. 91). Elsevier BV. https://doi.org/10.1016/b978-0-12-818598-8.00006-7

Khader, E. H., Mohammed, T. J., Mirghaffari, N., Salman, A. D., Juzsakova, T., & Abdullah, T. A. (2021). Removal of organic pollutants from produced water by batch adsorption treatment. Clean Technologies and Environmental Policy, 24(2), 713. https://doi.org/10.1007/s10098-021-02159-z

Khan, B., Burgess, R. M., & Cantwell, M. G. (2023). Occurrence and Bioaccumulation Patterns of Per- and Polyfluoroalkyl Substances (PFAS) in the Marine Environment. ACS ES&T Water, 3(5), 1243. https://doi.org/10.1021/acsestwater.2c00296

Kumar, R., Qureshi, M., Vishwakarma, D. K., Al-Ansari, N., Kuriqi, A., Elbeltagi, A., & Saraswat, A. (2022). A review on emerging water contaminants and the application of sustainable removal technologies [Review of A review on emerging water contaminants and the application of sustainable removal technologies]. Case Studies in Chemical and Environmental Engineering, 6, 100219. Elsevier BV. https://doi.org/10.1016/j.cscee.2022.100219

Kumar, V., Sharma, M., Sondhi, S., Kaur, K., Sharma, D., Sharma, S., & Utreja, D. (2023). Removal of Inorganic Pollutants from Wastewater: Innovative Technologies and Toxicity Assessment. Sustainability, 15(23), 16376. https://doi.org/10.3390/su152316376

Kumari, P., Bahadur, N., & Dumée, L. F. (2019). Photo-catalytic membrane reactors for the remediation of persistent organic pollutants – A review [Review of Photo-catalytic membrane reactors for the remediation of persistent organic pollutants – A review]. Separation and Purification Technology, 230, 115878. Elsevier BV. https://doi.org/10.1016/j.seppur.2019.115878

Kurwadkar, S., Dane, J., Kanel, S. R., Nadagouda, M. N., Cawdrey, R. W., Ambade, B., Struckhoff, G. C., & Wilkin, R. T. (2021). Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution [Review of Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution]. The Science of The Total Environment, 809, 151003. Elsevier BV. https://doi.org/10.1016/j.scitotenv.2021.151003

Lee, C., Lin, L.-S., Martínez-Huitle, C. A., & Pensini, E. (2025). Towards decentralized and sustainable water and wastewater treatment systems. Scientific Reports, 15(1). https://doi.org/10.1038/s41598-025-93897-3

Loganathan, P., Kandasamy, J., Ratnaweera, H., & Vigneswaran, S. (2024). Treatment Trends and Hybrid Methods for the Removal of Poly- and Perfluoroalkyl Substances from Water—A Review. Applied Sciences, 14(6), 2574. https://doi.org/10.3390/app14062574

Ludmer, Z., Golan, T., Ermolenko, E., Brauner, N., & Ullmann, A. (2008). Simultaneous Removal of Heavy Metals and Organic Pollutants from Contaminated Sediments and Sludges by a Novel Technology, Sediments Remediation Phase Transition Extraction. Environmental Engineering Science, 26(2), 419. https://doi.org/10.1089/ees.2007.0198

Lukić-Bilela, L., Matijošytė, I., Krutkevičius, J., Alexandrino, D. A. M., Šafařík, I., Burlakovs, J., Gaudêncio, S. P., & Carvalho, M. F. (2023). Impact of per- and polyfluorinated alkyl substances (PFAS) on the marine environment: Raising awareness, challenges, legislation, and mitigation approaches under the One Health concept [Review of Impact of per- and polyfluorinated alkyl substances (PFAS) on the marine environment: Raising awareness, challenges, legislation, and mitigation approaches under the One Health concept]. Marine Pollution Bulletin, 194, 115309. Elsevier BV. https://doi.org/10.1016/j.marpolbul.2023.115309

Martini, S., & Roni, K. A. (2021). The existing technology and the application of digital artificial intelligent in the wastewater treatment area: A review paper [Review of The existing technology and the application of digital artificial intelligent in the wastewater treatment area: A review paper]. Journal of Physics Conference Series, 1858(1), 12013. IOP Publishing. https://doi.org/10.1088/1742-6596/1858/1/012013

Marugán, J., Rodríguez-Chueca, J., Esplugás, S., Sans, C., & Malato, S. (2020). Removal of Pharmaceutically Active Compounds (PhACs) in Wastewater by Ozone and Advanced Oxidation Processes. In The handbook of environmental chemistry (p. 269). Springer Nature. https://doi.org/10.1007/698_2020_664

Matebese, F., Mosai, A. K., Tutu, H., & Tshentu, Z. R. (2024). Mining wastewater treatment technologies and resource recovery techniques: A review [Review of Mining wastewater treatment technologies and resource recovery techniques: A review]. Heliyon, 10(3). Elsevier BV. https://doi.org/10.1016/j.heliyon.2024.e24730

McQueen, A., Kimble, A., Krupa, P., Longwell, A., Calomeni, A. J., & Moore, D. W. (2025). Review of Emerging and Nonconventional Analytical Techniques for Per- and Polyfluoroalkyl Substances (PFAS): Application for Risk Assessment. Water, 17(3), 303. https://doi.org/10.3390/w17030303

Meegoda, J. N., Souza, B. B. de, Casarini, M. M., & Kewalramani, J. A. (2022). A Review of PFAS Destruction Technologies [Review of A Review of PFAS Destruction Technologies]. International Journal of Environmental Research and Public Health, 19(24), 16397. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/ijerph192416397

Mosbah, M. B., Mechi, L., Khiari, R., & Moussaoui, Y. (2020). Current State of Porous Carbon for Wastewater Treatment. Processes, 8(12), 1651. https://doi.org/10.3390/pr8121651

Nageeb, M. (2013). Adsorption Technique for the Removal of Organic Pollutants from Water and Wastewater. In InTech eBooks. https://doi.org/10.5772/54048

Nahar, K., Zulkarnain, N. A., & Niven, R. K. (2023). A Review of Analytical Methods and Technologies for Monitoring Per- and Polyfluoroalkyl Substances (PFAS) in Water [Review of A Review of Analytical Methods and Technologies for Monitoring Per- and Polyfluoroalkyl Substances (PFAS) in Water]. Water, 15(20), 3577. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/w15203577

Nakayama, S. F., Yoshikane, M., Onoda, Y., Nishihama, Y., Iwai-Shimada, M., Takagi, M., Kobayashi, Y., & Isobe, T. (2019). Worldwide trends in tracing poly- and perfluoroalkyl substances (PFAS) in the environment. TrAC Trends in Analytical Chemistry, 121, 115410. https://doi.org/10.1016/j.trac.2019.02.011

Nassazzi, W., Lai, F. Y., & Ahrens, L. (2022). A novel method for extraction, clean-up and analysis of per- and polyfluoroalkyl substances (PFAS) in different plant matrices using LC-MS/MS. Journal of Chromatography B, 1212, 123514. https://doi.org/10.1016/j.jchromb.2022.123514

Newman, B. (2025). Bench Test Report: Rapid Small-Scale Column Testing to Evaluate PFAS Treatment with CAST Pretreatment.

Ochoa-Herrera, V., & Sierra-Álvarez, R. (2008). Removal of perfluorinated surfactants by sorption onto granular activated carbon, zeolite and sludge. Chemosphere, 72(10), 1588. https://doi.org/10.1016/j.chemosphere.2008.04.029

Okiel, K., El-Sayed, M., & El-Kady, M. Y. (2011). Treatment of oil–water emulsions by adsorption onto activated carbon, bentonite and deposited carbon. Egyptian Journal of Petroleum, 20(2), 9. https://doi.org/10.1016/j.ejpe.2011.06.002

Panieri, E., Baralić, K., Đukić-Ćosić, D., Djordjević, A. B., & Saso, L. (2022). PFAS Molecules: A Major Concern for the Human Health and the Environment [Review of PFAS Molecules: A Major Concern for the Human Health and the Environment]. Toxics, 10(2), 44. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/toxics10020044

Pannu, M. W., Chang, J., Medina, R., Grieco, S. A., Hwang, M., & Plumlee, M. H. (2023). Comparing PFAS removal across multiple groundwaters for eight GACs and alternative adsorbent. AWWA Water Science, 5(3). https://doi.org/10.1002/aws2.1345

Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C. U., & Mohan, D. (2019). Pharmaceuticals of Emerging Concern in Aquatic Systems: Chemistry, Occurrence, Effects, and Removal Methods [Review of Pharmaceuticals of Emerging Concern in Aquatic Systems: Chemistry, Occurrence, Effects, and Removal Methods]. Chemical Reviews, 119(6), 3510. American Chemical Society. https://doi.org/10.1021/acs.chemrev.8b00299

Qu, J. (2008). Research progress of novel adsorption processes in water purification: A review [Review of Research progress of novel adsorption processes in water purification: A review]. Journal of Environmental Sciences, 20(1), 1. Elsevier BV. https://doi.org/10.1016/s1001-0742(08)60001-7

Radjenović, J., Petrović, M., & Barceló, Damià. (2006). Analysis of pharmaceuticals in wastewater and removal using a membrane bioreactor. Analytical and Bioanalytical Chemistry, 387(4), 1365. https://doi.org/10.1007/s00216-006-0883-6

Roccaro, P. (2018). Treatment processes for municipal wastewater reclamation: The challenges of emerging contaminants and direct potable reuse. Current Opinion in Environmental Science & Health, 2, 46. https://doi.org/10.1016/j.coesh.2018.02.003

Satyam, S., & Patra, S. (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review [Review of Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review]. Heliyon, 10(9). Elsevier BV. https://doi.org/10.1016/j.heliyon.2024.e29573

Silva, M. D., Cao, G., & Tam, K. C. (2025). Nanomaterials for the Removal and Detection of Heavy Metals: A Review [Review of Nanomaterials for the Removal and Detection of Heavy Metals: A Review]. Environmental Science Nano. Royal Society of Chemistry. https://doi.org/10.1039/d4en01041h

Smith, S. J., Lauria, M. Z., Ahrens, L., McCleaf, P., Hollman, P., Seroka, S. B., Hamers, T., Arp, H. P. H., & Wiberg, K. (2023). Electrochemical Oxidation for Treatment of PFAS in Contaminated Water and Fractionated Foam─A Pilot-Scale Study. ACS ES&T Water, 3(4), 1201. https://doi.org/10.1021/acsestwater.2c00660

Thoma, E. D., Wright, R., George, I., Krause, M. J., Presezzi, D., Villa, V., Preston, W., Deshmukh, P., Kauppi, P., & Zemek, P. G. (2021). Pyrolysis processing of PFAS-impacted biosolids, a pilot study. Journal of the Air & Waste Management Association, 72(4), 309. https://doi.org/10.1080/10962247.2021.2009935

Topolovec, B., Jovanović, O., Puač, N., Škoro, N., Lumbaque, E. C., & Petrović, M. (2024). Plasma water treatment for PFAS: Study of degradation of perfluorinated substances and their byproducts by using cold atmospheric pressure plasma jet. Journal of Environmental Chemical Engineering, 12(3), 112979. https://doi.org/10.1016/j.jece.2024.112979

Trojanowicz, M., & Koc, M. (2013). Recent developments in methods for analysis of perfluorinated persistent pollutants. Microchimica Acta, 180, 957. https://doi.org/10.1007/s00604-013-1046-z

Verma, S., Lee, T., Sahle-Demessie, E., Ateia, M., & Nadagouda, M. N. (2022). Recent advances on PFAS degradation via thermal and nonthermal methods. Chemical Engineering Journal Advances, 13, 100421. https://doi.org/10.1016/j.ceja.2022.100421

Wang, H., Gao, X., & Zuo, Y. (2024). Research and Application of Water Treatment Technologies for Emerging Contaminants (ECs): A Pathway to Solving Water Environment Challenges. Water, 16(13), 1837. https://doi.org/10.3390/w16131837

Xi, B., Dinkla, I. J. T., & Muyzer, G. (2022). Microbial ecology of biofiltration used for producing safe drinking water [Review of Microbial ecology of biofiltration used for producing safe drinking water]. Applied Microbiology and Biotechnology, 106, 4813. Springer Science+Business Media. https://doi.org/10.1007/s00253-022-12013-x

Xiao, F., Sasi, P. C., Alinezhad, A., Sun, R., & Ali, M. A. (2023). Thermal Phase Transition and Rapid Degradation of Forever Chemicals (PFAS) in Spent Media Using Induction Heating. ACS ES&T Engineering, 3(9), 1370. https://doi.org/10.1021/acsestengg.3c00114

Zamora-Ledezma, C., Negrete-Bolagay, D., Figueroa, F., Zamora-Ledezma, E., Ni, M., Alexis, F., & Guerrero, V. H. (2021). Heavy metal water pollution: A fresh look about hazards, novel and conventional remediation methods. Environmental Technology & Innovation, 22, 101504. https://doi.org/10.1016/j.eti.2021.101504

Zheng, Y., Wan, Y., Zhang, Y., Huang, J., Yang, Y., Tsang, D. C. W., Wang, H., Chen, H., & Gao, B. (2022). Recovery of phosphorus from wastewater: A review based on current phosphorous removal technologies [Review of Recovery of phosphorus from wastewater: A review based on current phosphorous removal technologies]. Critical Reviews in Environmental Science and Technology, 53(11), 1148. Taylor & Francis. https://doi.org/10.1080/10643389.2022.2128194