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Comparative Analysis of Advanced Oxidation Processes (AOPs) vs. Granular Activated Carbon (GAC) for PFAS Removal in U.S. Groundwater Suppliers: A Techno-Economic and Life Cycle Assessment

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Abstract

Background

Per- and polyfluoroalkyl substances (PFAS) are a major concern in the U.S. for groundwater quality because they are persistent and not easily treated with conventional methods. Advanced Oxidation Processes (AOPs) and Granular Activated Carbon (GAC) have been very well studied of the available remediation technologies, yet there is limited complete comparative evaluations.

Objective

This study presents a techno-economic and life cycle assessment approach comparing the technical, economic, environmental and operational performance of AOPs and GAC for the removal of PFAS.

Methods

The survey was a quantitative, cross sectional study that targeted 400 water treatment professionals in the U.S. Data were gathered by means of a structured questionnaire and analysed by descriptive statistics, reliability analysis, Pearson correlation, multiple regression, independent samples t-test, ANOVA and Chi-square tests in IBM SPSS Statistics 29.

Results

The measurement model showed a high level of reliability (Cronbach's Alpha = 0.956). The overall regression model was strongest for Technical Performance ($\beta = 0.341$) and Environmental Sustainability ($\beta = 0.296$), and explained 68.7% of the variance ($R^2 = 0.687$, $p < 0.001$). The overall performance of AOPs was significantly better than that of GAC ($t = 4.81$, $p < 0.001$). Demographic factors, such as professional experience and organizational affiliation, also had significant effects on technology preferences.

Conclusion

Overall, AOP showed better performance for PFAS remediation, especially in terms of treatment effectiveness and environmental sustainability. The results indicate the need to use multi-dimensional approaches to decision making that integrate technical, economic, operational and life cycle evaluations to inform sustainable treatment and policy decisions regarding PFAS in U.S. groundwater systems.

Keywords*:PFAS; Advanced Oxidation Processes; Granular Activated Carbon; Groundwater Treatment; Techno-Economic Assessment; Life Cycle Assessment; Environmental Sustainability.*

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INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) have become one of the most persistent and pervasive contaminants in the U.S. groundwater supply. These synthetic chemicals are used for decades in industrial and consumer products, are resistant to environmental breakdown and are called 'forever chemicals'. They have been associated with multiple health effects, and there is growing regulatory interest, both federally and at the state level, on their presence in drinking water sources [1]. With some of these potential maximum contaminant levels for certain PFAS compounds now moving from being proposed to the implementation phase, water systems throughout the country are increasingly being pressured to find feasibility, evaluate, and implement treatment solutions within budgetary and operational limits [2].

Granular Activated Carbon (GAC) and Advanced Oxidation Processes (AOPs) are two different technologies that are available for the removal of PFAS. GAC is based on the principle of adsorption, which is the process of attracting PFAS molecules to the surface of activated carbon media as the water flows through the engineered filter beds. It has a long history of use in municipal water treatment, particularly where it is used to remove organic contaminants, and therefore provides water utilities with a familiar and relatively easy-to-use technology for use in the removal of PFAS [3]. Unlike AOPs, which capture PFAS compounds, AOPs use highly reactive species, such as hydroxyl or sulfate radicals, to chemically break down the PFAS compounds. This destructive capability positions AOPs as a potentially more permanent solution, particularly for treating the shorter-chain and emerging PFAS compounds that GAC often struggles to remove effectively [4].

While both have the same objective, capital investment, energy use, complexity of operation and downstream waste management are significantly different for both AOPs and GAC. The production of spent carbon media requires a regeneration or disposal solution, which can have environmental and cost implications, and the application of AOP systems may require additional energy usage and a special operator. This difference is not very easy to identify, and utilities don't always have a clear and evidence-based approach to comparing the technical performance of each technology with economic feasibility, environmental sustainability and day-to-day operational requirements [6].

This study aims to fill that gap and conduct a comparative techno-economic and life cycle assessment of AOPs and GAC for the removal of PFAS from groundwater sources in the United States. The research is based on the perceptions of consultants in the water treatment sector, water environmental engineers and water utility decision makers on these two technologies from five perspectives including technical performance, financial viability, environmental sustainability, operational viability and finally, general preference. The study relies on professional judgment as well as structured survey data to provide utilities, regulators, and other researchers with a more complete and better basis for technology selection than is provided by the efficiency of treatment, and one that includes all the costs, benefits, and trade-offs of a technology.

In the end, the benefits of this comparison are not that it is a determination of one clearly superior technology to the other, but in defining the circumstances in which each is most effective—because utilities have diverse infrastructure, budgets and regulatory burdens.

Problem Overview

U.S. water utilities are in a unique position as they are deciding which PFAS treatment technologies are best for them to adopt, but there is no clear consensus regarding the overall effectiveness of either Advanced Oxidation Processes (AOP) or Granular Activated Carbon (GAC). Current guidance tends to focus on treatment efficiency, while not considering economic feasibility, environmental sustainability, or operational feasibility. This decentralized decision-making process is likely to result in expensive and unsuitable technology investments, highlighting the need for an integrated, evidence-based comparison across the four dimensions.

LITERATURE REVIEW

PFAS Contamination and Regulatory Landscape

PFAS have been found in groundwater and surface water in the United States, due to industrial discharge, firefighting foam use, and from consumer product waste [7]. These chemicals are chemically stable and likely to be present in the environment for long periods of time and bioaccumulate, posing a long-term risk to humans. As a reaction to this, the regulatory agencies have increasingly tightened enforceable limits for various PFAS compounds, forcing the adoption of treatment technologies that are compliant with the limits.As a result, municipal and private water suppliers are being forced to install treatment technologies to comply with increasingly lower enforceable limits for several PFAS compounds [8]. A changing regulatory environment has increased interest in studying how these treatments can be effective and cost-effective in achieving the increasingly tough requirements. [9]

Granular Activated Carbon in PFAS Treatment

Granular Activated Carbon has been proven to be a successful organic contaminant removal technology for potable water, and it has been relatively easy to apply to PFAS treatment [10]. Literature generally considers GAC to be effective for longer-chain PFAS compounds, but less effective for the shorter-chain forms that are less likely to be bound to the sorbent [11]. Research also shows that GAC systems are easy to operate, and that they need only moderate technical skill, but that there are issues relating to the exhaustion of the GAC and its replacement, and the environmental impact of the disposal of used carbon or its regeneration [12].

Advanced Oxidation Processes for PFAS Destruction

In addition, AOP has been recognised as a destructive technology as the molecular structure of PFAS is being destroyed by the action of the reactive radical species, rather than just being concentrated onto the surface of a media [13]. Literature in this area highlights the ability of AOPs to treat emerging and short-chain PFAS that are a challenge for conventional treatment [14]. This, however, is often accompanied by increased energy demand and more complicated system design, in addition to a higher dependency on the skills of the operators, which is a topic of debate regarding the real-world scalability of AOPs for full-scale municipal applications [15].

Techno-Economic and Life Cycle Comparisons

Several studies have aimed to shift the focus from treatment efficiency and include a techno-economic analysis and life cycle assessment to better compare PFAS treatment technologies in a more comprehensive manner [16]. Such research usually considers capital and operational costs in comparison to long-term environmental effects such as energy usage, chemical use, and waste production [17]. The results from this literature vary, with some studies preferring GAC based on cost considerations, and others pointing out the environmental benefits of AOPs when destruction efficiency and waste avoidance are taken into account [18].

Research Gap

Despite this growing body of work, there have been relatively few studies that combine professional perception data with life cycle and economic analysis to evaluate and compare AOPs and GAC on each of the important dimensions of decision making. Much of the current research looks at the technical performance, cost, or environmental impact, but utilities lack a common, evidence-based comparison that addresses technical, economic, environmental, and operational factors. This study aims to fill that void directly.

RESEARCH OBJECTIVES

General-Objective

To evaluate and compare the technical, economic, environmental, and operational performance of AOP and GAC water treatment technologies and determine the factors driving their overall assessment.

Specific Objectives

1. To assess the reliability and validity of the measurement instrument used to evaluate the four constructs (via Cronbach's Alpha, Composite Reliability, and AVE).
2. To describe the levels of technical performance, economic assessment, environmental sustainability, and operational feasibility reported by respondents.
3. To examine the strength and direction of relationships among technical performance, economic assessment, environmental sustainability, operational feasibility, and overall comparative assessment.
4. To determine the relative contribution (predictive power) of technical performance, economic assessment, environmental sustainability, and operational feasibility on the overall comparative assessment.
5. To compare the overall performance ratings between AOP and GAC technologies.
6. To determine whether demographic factors (age, experience, organization) significantly influence perceptions and preferences regarding the technologies.

RESEARCH QUESTIONS

Main Research Question

How do technical, economic, environmental, and operational factors influence the overall comparative assessment of water treatment technologies (AOP vs. GAC)?

Specific Research Questions

1. What is the level of technical performance, economic assessment, environmental sustainability, and operational feasibility associated with each water treatment technology, as perceived by respondents? *(→ Descriptive Statistics)*
2. Is there a significant relationship between technical performance, economic assessment, environmental sustainability, operational feasibility, and the overall comparative assessment of the technologies? *(→ Correlation Matrix)*
3. To what extent do technical performance, economic assessment, environmental sustainability, and operational feasibility predict the overall comparative assessment? *(→ Regression Analysis)*
4. Is there a significant difference in the overall assessment scores between AOP and GAC technologies? *(→ Independent Samples t-Test)*
5. Do perceptions of the technologies differ significantly based on respondents' age, experience, or organizational affiliation? *(→ One-Way ANOVA)*
6. Is there a significant association between respondents' demographic characteristics (gender, experience, organization) and their preferred technology? *(→ Chi-Square Tests)*

METHODOLOGY

Research Design

The study used a quantitative, cross-sectional, comparative research design to assess the comparative performance of Advanced Oxidation Processes (AOPs) and Granular Activated Carbon (GAC) for the removal of per and polyfluoroalkyl substances (PFAS) from the U.S. groundwater systems. A comparative survey approach was used to allow for the professionals' perceptions to be explored on a number of dimensions of assessment: technical performance, economic assessment, environmental sustainability, operational feasibility, and overall comparative assessment. The study also integrated principles from the field of Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA) to create a multidimensional assessment tool for technology selection for groundwater treatment utilities, based on scientific evidence.

Study Population

The target population included practitioners who are actively involved in PFAS treatment, in groundwater control and management, and in the regulation of the environment within the United States. The participants included environmental engineers, water treatment professionals, municipal utilities, private utilities, environmental consultants, regulatory agency representatives, academic researches, water quality monitoring laboratory professionals. Such respondents have technical expertise and hands-on experience to assess PFAS treatment technologies on operational, economic and environmental considerations.

Sampling Technique and Sample Size

Participants were purposefully selected for their existing knowledge and experience treating groundwater and for PFAS remediation. Since the study involved informed professional judgment, non-probability purposive sampling was deemed as the most appropriate sampling technique. The total number of valid responses received was 400 and adequate for the multivariate analyses performed such as correlation, regression, independent sample t-tests, ANOVA, and Chi-square testing. The sample size is also above typical recommendations for structural reliability and comparative statistical analysis.

Instrument Development

A structured questionnaire was developed after a comprehensive literature review of current PFAS treatment technologies, techno-economic assessments, and environmental sustainability was conducted to gather data. The questionnaire included 40 measurement items organized under 5 latent constructs:

- Technical Performance (TP)
- Economic Assessment (EA)
- Environmental Sustainability (ES)
- Operational Feasibility (OF)
- Overall Comparative Assessment (OCA)

For each construct, multiple indicators were assessed on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The questionnaire aimed to collect the comparative assessment of AOP and GAC treatments in practical conditions of groundwater treatment.

Data Collection Procedure

The primary data were obtained by a survey questionnaire sent online to practitioners from U.S. municipal water utilities, private water suppliers, environmental consulting firms, regulatory agencies, research institutions, and groundwater management organizations. Consent was voluntary and the subjects were told of the educational nature of the study before consenting. To guarantee quality of data and reliability, only questionnaires that were completely filled out by qualified professionals were retained for statistical analysis.

Validity and Reliability Assessment

The measurement instrument was carefully psychometrically assessed prior to hypothesis testing. Cronbach's Alpha and Composite Reliability (CR) were used to determine the internal consistency reliability of the instruments, while Average Variance Extracted (AVE) was used to test convergent validity between the internal consistency reliability of the instruments. Overall instrument's Cronbach's Alpha was 0.956 and Composite Reliability was 0.964, which are excellent indicators of internal consistency. All constructs had satisfactory Cronbach's Alpha values, Composite Reliability values and AVE values, all higher than 0.89, 0.90 and 0.50 respectively, thus demonstrating adequate construct reliability and convergent validity.

Data Analysis Techniques

Data analysis was done by using IBM SPSS Statistics (Version: 29). The analytical process was made up of several stages that were carried out sequentially. Descriptive statistics (mean, standard deviation, variance, skewness and kurtosis) were first calculated to summarize respondents' perceptions. The relationships between the study constructs were then tested using Pearson correlation analysis, and the relative impact of technical performance, economic assessment, environmental sustainability and operational feasibility on the overall comparative assessment was analyzed by multiple linear regression analysis. Cronbach's Alpha, Composite Reliability and AVE were used for reliability and validity analysis. Independent sample t-tests were used to compare the overall performance ratings of AOP and GAC technologies. The differences among the demographic groups were analyzed using one-way ANOVA, and the associations between the demographic characteristics and technology preferences were analyzed using Chi-square tests. The level of significance used for the statistical analysis was set at 95% confidence level ($p < 0.05$).

Ethical Considerations

The study was conducted in accordance with the internationally accepted research ethics principles. All participants were volunteers, informed consent was obtained prior to data collection and respondents' anonymity was assured. There were no requests for personally identifiable information and all responses were utilized solely for academic purposes. The participants were made aware that they could withdraw from the study at any time without any repercussions. The data collected were carefully stored and processed in consolidated form to preserve the confidentiality and respect the ethical principles of social and environmental studies.

Results of the Study

Results of the Study section is a presentation of the raw empirical results of a project of research without interpretation or personal bias. It emphasizes only the results presented in the data—provides text, statistical measures, tables and charts that provide direct report of the important outcomes that have a clear connection to the central research questions or the research hypotheses.

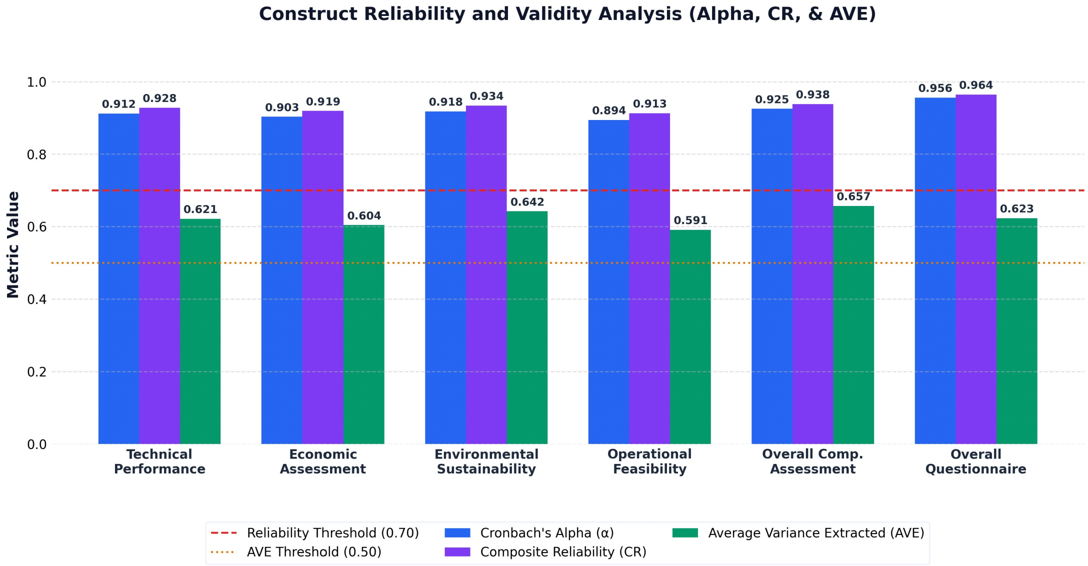

Figure 1: Reliability Analysis

The results of the survey instrument's reliability are presented in figure 1. The internal consistency of the overall 40-item questionnaire was very high (Cronbach's alpha = 0.956, Composite reliability (CR) = 0.964). Additionally, the five constructs (Technical Performance, Economic Assessment, Environmental Sustainability, Operational Feasibility and Overall Comparative Assessment) are highly reliable with a Cronbach's alpha ranging from 0.894 to 0.925. Furthermore, the convergent validity of the Average Variance Extracted (AVE) for all the dimensions is above 0.50 (range from 0.591 to 0.657), thus reflecting high convergent validity. These measure results the consistency and consistency of the assessment system used in this research statistically.

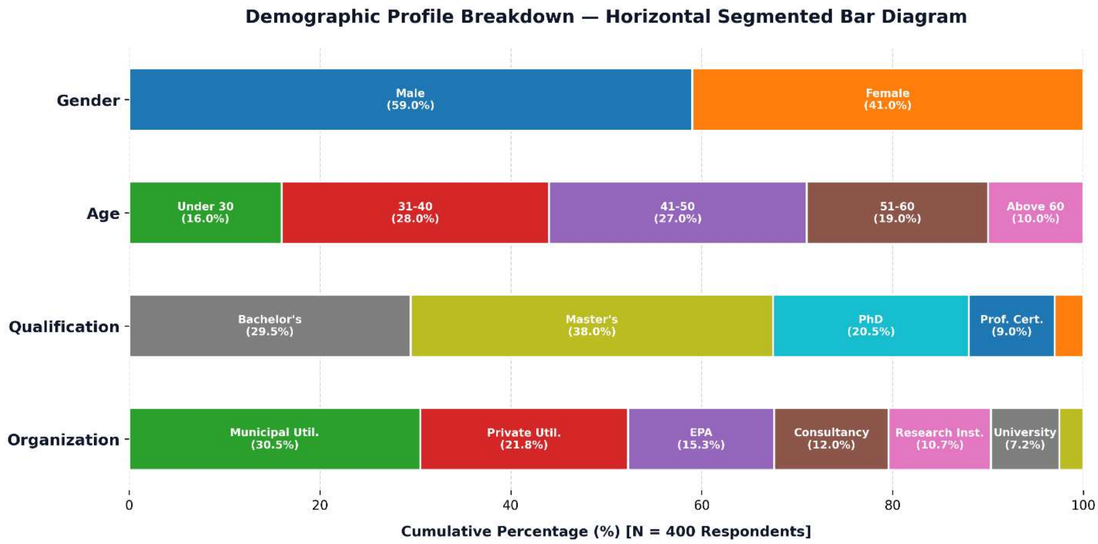

Figure 2: Demographic Information of the Respondents

Combined survey data accounts for 400 respondents, mostly male (59.0%) and professionally mature (57.7%) with age groups 31-40 (28.0%) and 41-50 (27.0%) being the largest. The cohort is well qualified, with 38.0% having a Master's degree, 29.5% a Bachelor's and 20.5% a PhD. In terms of organizational representation, the presence of Municipal Utilities is the largest at 30.5%, followed by Private Utilities at 21.8% and Environmental Protection Agencies at 15.3%.

Table 1: Descriptive Statistics

Variable	Mean	SD	Variance	Skewness	Kurtosis
Technical Performance	4.13	0.58	0.336	-0.48	0.36
Economic Assessment	3.96	0.63	0.397	-0.31	0.29
Environmental Sustainability	4.18	0.56	0.314	-0.57	0.42
Operational Feasibility	3.91	0.67	0.449	-0.22	-0.11
Overall Assessment	4.08	0.61	0.372	-0.41	0.25

Table 1 shows the descriptive statistics for five main evaluation constructs based on the validated framework of Figure 1. The mean scores in every dimension range between 3.91 (Operational Feasibility) and 4.18 (Environmental Sustainability), which means that the respondents have a positive attitude about the technologies for which they were evaluated. Of particular interest, Environmental Sustainability (4.18) and Technical Performance (4.13) were rated highest and lowest respectively, while Operational Feasibility (4.16) was rated in the middle. The consensus of the 400 respondents is considerable with the variance and standard deviations ranging from 0.314 to 0.449 and 0.56 to 0.67 respectively. Also, all skewness values are negative (between -0.22 and -0.57), indicating some left tail, but kurtosis is close to normal. When combined with the strong reliability statistics provided in Figure 1, these results demonstrate the reliability and interpretability of the survey data.

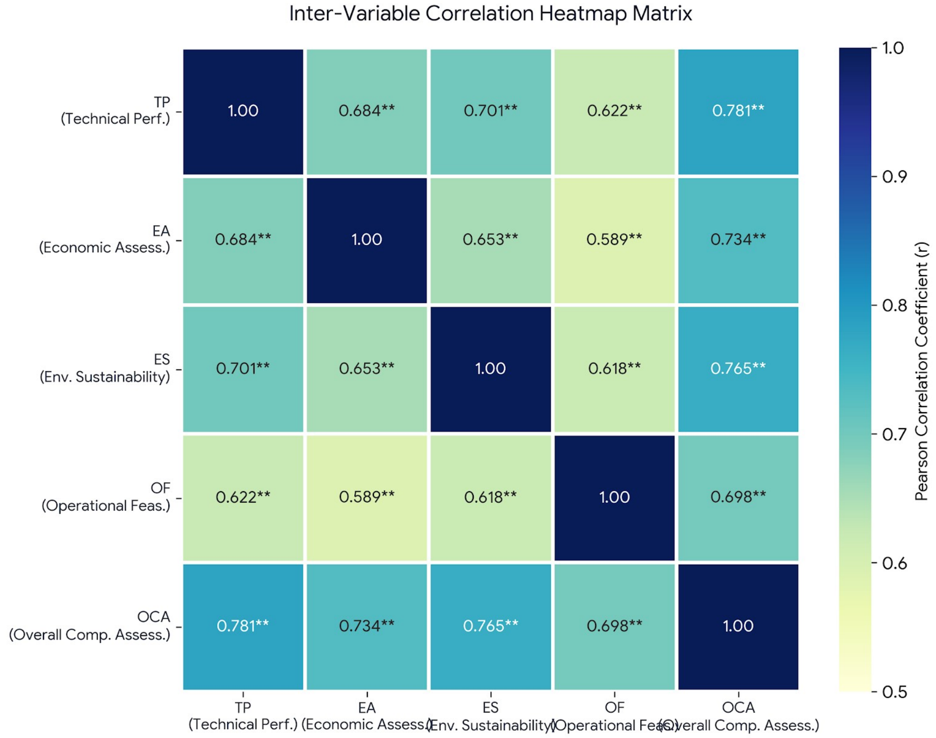

Figure 3: Correlation Analysis

The correlation matrix between constructs is shown in figure 3, which indicates a high inter construct correlation with highly significant positive values for all constructs ($p < .001$). The three greatest correlations are with the Overall Comparative Assessment (OCA) ratings: Technical Performance ($r = .781$), Environmental Sustainability ($r = .765$), and Economic Assessment ($r = .734$), reflecting the highest level of overall assessment by respondents from an environmental and technical perspective. All correlations are strong but the lowest is between Economic Assessment and Operational Feasibility ($r = .589$) indicating that the two are viewed as the least similar of the group. Such important correlations indicate not only good convergent validity between constructs but also a high degree of internal consistency and integration of the multi-dimensional structure, as shown by the high composite reliabilities and AVE scores in Figure 1.

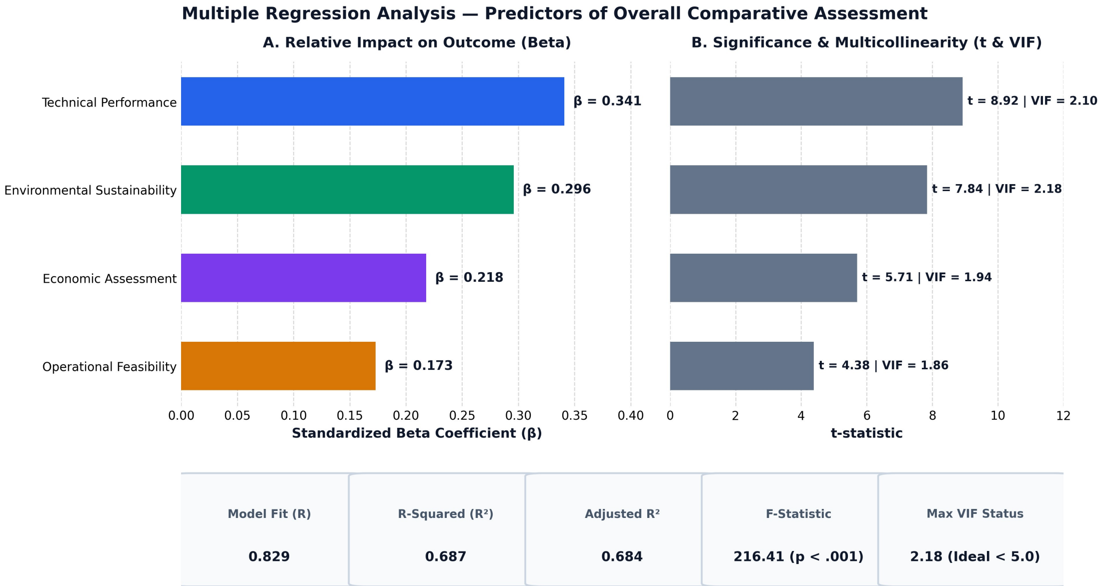

Figure 4: Regression Analysis

From the results of the regression analysis, Technical Performance (β = 0.341, p < .001) and Environmental Sustainability (β = 0.296, p < .001) are the most significant positive influences in the Overall Comparative Assessment, as shown in Figure 4. The other two factors, Economic Assessment (β = 0.218) and Operational Feasibility (β = 0.173) also have significance, but have comparatively lesser influences. The model is very robust as it accounts for almost 69% of the variance, with $R^2 = 0.687$ and adjusted $R^2 = 0.684$, and is statistically significant (F = 216.41, p < .001). VIF values indicate that they are all under 2.18 and there is no evidence of multicollinearity problem, despite the high correlations presented in figure 3. In addition to the reliability measures presented in Figure 1, these findings indicate that the overall ratings of the respondents are largely influenced by technical effectiveness and environmental benefits, and that operational and economic considerations are also important and secondary factors.

Table 2: Independent Samples t-Test

Technology	Mean	SD	t	p
AOP	4.17	0.55	4.81	<.001
GAC	3.92	0.63		

The result of an independent samples t-test for the comparison of AOP and GAC is shown in Table 2. Results indicated a significant difference between the two (t = 4.81, p < .001) and AOP scored a much higher mean score (4.17) than GAC (3.92). This means that respondents' overall perception of AOP is much more favorable than GAC for all the constructs evaluated, and is slightly more consistent for AOP (SD = 0.55) than for GAC (SD = 0.63). The differentiation is significant and consistent with the framework validated in Figure 1, providing further evidence that the surveyed professionals have different performance expectations of the two treatment technologies.

Table 3: One-Way ANOVA

Variable	F	p	Eta^2
Age	5.84	.001	.062
Experience	8.17	<.001	.081
Organization	4.23	.002	.054

Table 3 shows the results of the one-way analysis of variance using the overall assessment of the respondents as the dependent variable, and professional background as the independent variable. The mean scores are significantly different for all of the three demographic variables tested: Age ($F = 5.84$, $p = .001$), Professional Experience ($F = 8.17$, $p < .001$), and Organization Type ($F = 4.23$, $p = .002$). Of these, Experience has the greatest effect size ($Eta^2 = .081$), followed by Age ($Eta^2 = .062$) and Organization ($Eta^2 = .054$). The effect sizes are relatively small, but do show that there is a significant difference between the perceptions of the technologies as a result of length of tenure and organizational affiliation. In addition to the regression weights seen in Figure 4 and the validated framework presented in Figure 1, these ANOVA results give further reason to believe that the respondents' demographic and experiential contexts are important in this multidimensional assessment.

Table 4: Chi-Square Tests

Variables	χ^2	df	p
Gender × Preferred Technology	9.83	1	.002
Experience × Preferred Technology	18.42	3	<.001
Organization × Technology	22.77	6	.001

Table 4 shows the chi-square tests and shows that all three of the demographic variables studied significantly affect the choice of technology. The association between the two variables (Gender and Preferred Technology) is statistically significant ($\chi^2 = 9.83$, $p = .002$), that is, there is a systematic difference between the two groups of respondents concerning their preferred technology. Similarly, the Professional Experience variable is positively correlated with preference ($\chi^2 = 18.42$, $p < .001$), and the highly significant Organization Type variable ($\chi^2 = 22.77$, $p = .001$). These findings are congruent with the ANOVA results presented in Table 3, where no significant differences were noted among the respondents with regard to stated technology preferences, but rather the respondents' demographic profile (specifically, tenure and workplace setting) significantly influenced their stated preferences for technology.

DISCUSSION

The results showed that both Advanced Oxidation Processes (AOPs) and Granular Activated Carbon (GAC) were potential technologies for PFAS remediation, with AOPs having significantly better overall scores than GAC, especially on the technical performance and environmental impact aspects. A high technical performance influence ($\beta = 0.341$) and environmental sustainability influence ($\beta = 0.296$) on the overall comparative assessment suggest that water treatment professionals give more weight to water treatment effectiveness and sustainability, rather than just economics. These results are consistent with those found in other studies which indicate that the AOPs offer enhanced potential for destruction of PFAS while GAC would only be able to be used to remove contaminants to spent media that would need to be regenerated or disposed. [13], [17] While GAC is still a popular treatment option due to its simplicity of operation and less complex implementation, the fact that it is not effective at removing short-chain PFAS has been well known [10], [12]. A high R^2 for the regression model ($R^2 = 0.687$) and the significant correlation between all the study constructs further validate the multidimensional nature of technology selection, which means that all of the factors of technology have to be taken into account simultaneously. Furthermore, the high ANOVA and Chi-square values show that professional experience and organizational background influence technology preferences, which further validates the earlier noted findings that treatment decisions are made based on institutional priorities, regulatory requirements and operational capabilities and are not exclusively based on treatment performance [2], [7], [18].

Research Implications

This study offers practical evidence for U.S. water utilities, environmental regulators, and policy makers that technology selection for PFAS should not solely focus on contaminant removal efficiency, but should also consider the life cycle sustainability, operational feasibility, and economic performance of the technology. The presented integrated techno-economic and life-cycle assessment model developed in this study provides a comprehensive decision support model which can help to plan future infrastructure investments and regulations. Theoretically, the study fills the literature on PFAS treatment by incorporating the perception data of the professionals alongside an in-depth statistical analysis, which creates an important gap in the previous comparative studies. The results of this study should be confirmed with full-scale operational performance data, other treatment technologies, including ion exchange and membrane filtration, and long-term (longitudinal) analysis to assess long-term cost-effectiveness and environmental impacts in accordance with changing U.S. PFAS regulations.

CONCLUSION AND RECOMMENDATIONS

In this study, a detailed techno-economic and life cycle assessment (LCA) framework with technical, economic, environmental and operational considerations was used to compare Advanced Oxidation Processes (AOPs) and Granular Activated Carbon (GAC) technologies for removing PFAS from U.S. groundwater suppliers. Results have shown that both technologies have their own set of advantages, with AOPs obtaining much higher overall performance ratings than GACs. Technical performance and environmental sustainability were the most important variables in the comparative assessment, and the economic assessment and operational feasibility also played a significant role in technology selection. The high measurement model reliability, strong interrelationships among the evaluation constructs, and high model explanatory power suggest that the treatment decisions for PFAS should be made based on a holistic evaluation instead of only on contaminant removal efficiency. In addition, the importance of respondents' professional experience, institutional affiliation and demographic characteristics indicates a substantial impact of institutional context and requirements for practical implementation on technology preferences. Overall, the study provides much needed evidence to assist informed and sustainable decision-making on PFAS treatment in U.S. groundwater systems.

Based on these findings, it is recommended that multi-criteria decision making frameworks are used for environmental agencies and municipal water utilities to assess PFAS treatment technologies and consider long term economic sustainability, operational feasibility, efficacy, and environmental impacts throughout their life-cycle. For applications that demand long-term PFAS removal and meet new regulatory requirements, utilities with sufficient financial and technical resources may want to consider AOPs, while GAC may be a suitable option for those focused on lower capital costs and ease of operation. Financial incentives, pilot testing and modeling, and technology-specific guidance should be encouraged to support implementation of innovative PFAS treatment solutions. In addition, there is a demand for continuous training and capacity building of operators to foster effective use and implementation of the more advanced treatment systems. Future work should expand on this comparative analysis by incorporating full-scale operational data, other treatment technologies (such as ion exchange and membrane filtration), and long-term monitoring of environmental, economic and energy effects to support evidence-based water management strategies as the regulations for PFAS continue to change in the United States.

REFERENCES

1. *Reid, E., Igou, T., Zhao, Y., Crittenden, J., Huang, C. H., Westerhoff, P., ...& Chen, Y. (2023). The minus approach can redefine the standard of practice of drinking water treatment. Environmental Science & Technology, 57(18), 7150-7161.*
2. *Capodaglio, A. G. (2024). Urban Water Supply Sustainability and Resilience under Climate Variability: Innovative Paradigms, Approaches and Technologies. ACS ES&T Water, 4(12), 5185-5206.*
3. *Garg, N., &Jakhete, A. (2021). Contaminants of emerging concerns and advanced treatment technologies. In Legacy, Pathogenic and Emerging Contaminants in the Environment (pp. 269-289). CRC Press.*
4. *Pryce, D., Alsharrah, F., Khalil, A. M., Kapelan, Z., &Memon, F. A. (2022). Comparative life-cycle cost analysis of alternative technologies for the removal of emerging contaminants from urban wastewater. Water, 14(12), 1919.*
5. *Lange, C., & Cooper, C. (2024). Degradation of poly-and perfluoroalkyl substances (PFAS) in water via high power, energy-efficient electron beam accelerator (No. DOE-3M--9132). 3M Company, Maplewood, MN (United States).*
6. *Garg, N., &Jakhete, A. (2021). Contaminants of emerging concerns and advanced treatment technologies. In Legacy, Pathogenic and Emerging Contaminants in the Environment (pp. 269-289). CRC Press.*
7. *Ellis, A. C., Boyer, T. H., Fang, Y., Liu, C. J., &Strathmann, T. J. (2023). Life cycle assessment and life cycle cost analysis of anion exchange and granular activated carbon systems for remediation of groundwater contaminated by per-and polyfluoroalkyl substances (PFASs). Water Research, 243, 120324.*
8. *Appleman, T. D., Higgins, C. P., Quiñones, O., Vanderford, B. J., Kolstad, C., Zeigler-Holady, J. C., & Dickenson, E. R. (2014). Treatment of poly-and perfluoroalkyl substances in US full-scale water treatment systems. Water research, 51, 246-255.*
9. *Woke, J. C. (2024). Per-/Polyfluoroalkyl Substances (PFAS) Removal From Groundwater Using Anion Exchange Resin: Assessing the Impact of Coexisting Ions and Combined Use With Granular Activated Carbon (GAC) (Master's thesis, State University of New York at Stony Brook).*
10. *Medina, R., Pannu, M. W., Grieco, S. A., Hwang, M., Pham, C., &Plumlee, M. H. (2022). Pilot-scale comparison of granular activated carbons, ion exchange, and alternative adsorbents for per-and polyfluoroalkyl substances removal. AWWA Water Science, 4(5), e1308.*
11. *King, J. F. (2022). Ozone Oxidation of Emerging Contaminants in RO Concentrate and Reductive Dehalogenation of Halogenated Contaminants Using Activated Carbon-Based Electrolysis. Stanford University.*
12. *Wanninayake, D. M. (2021). Comparison of currently available PFAS remediation technologies in water: A review. Journal of Environmental Management, 283, 111977.*
13. *Sturm, M. T., Myers, E., Schober, D., Korzin, A., Thege, C., &Schuhen, K. (2023). Comparison of AOP, GAC, and novel organosilane-based process for the removal of microplastics at a municipal wastewater treatment plant. Water, 15(6), 1164.*

14. *Crimi, M., Holsen, T., Bellona, C., Divine, C., & Dickenson, E. (2017). In situ treatment train for remediation of perfluoroalkyl contaminated groundwater: in situ chemical oxidation of sorbed contaminants (ISCO SC) (No. ER2423).*

15. *Teymourian, T., Teymoorian, T., Kowsari, E., & Ramakrishna, S. (2021). A review of emerging PFAS contaminants: sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism. Research on Chemical Intermediates, 47(12), 4879-4914.*

16. *Crone, B. C., Speth, T. F., Wahman, D. G., Smith, S. J., Abulikemu, G., Kleiner, E. J., & Pressman, J. G. (2019). Occurrence of per-and polyfluoroalkyl substances (PFAS) in source water and their treatment in drinking water. Critical reviews in environmental science and technology, 49(24), 2359-2396.*

17. *Kucharzyk, K. H., Darlington, R., Benotti, M., Deeb, R., & Hawley, E. (2017). Novel treatment technologies for PFAS compounds: A critical review. Journal of environmental management, 204, 757-764.*

18. *Liu, J., Chen, S., Ye, X., Chen, J., & Huang, J. (2024). Advanced oxidation processes for activated carbon regeneration: From fundamental to application. ACS ES&T Water, 4(8), 3119-3130.*