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Democratising PFAS Remediation: Low-Cost GAC/Ion Exchange Systems for Rural Communities

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Abstract
The research presents a review of low-cost PFAS remediation technologies such as granular activated carbon (GAC) and ion exchange (IX) systems, in water communities in rural and small populations and the opportunities of the new EPA rule on PFAS in 2024. A second qualitative literature review of reputable sources underlines the efficiency of GAC and IX removal systems of long- and short-chain PFAS, where IX is found to possess greater adsorption capacity and longer working time, but uncertainties still exist with variable natural waters. Available literature emphasises the importance of long empty bed contact times (EBCT) on GAC to short-chain PFAS, and it singles out the cost and operating issues of the two technologies. The potential solutions are also discussed: hybrid treatment systems and new adsorbents. The major gaps are the lack of information about mixtures of PFAS, in particular at GenX compounds, and the feasibility of rural water supplies characterised by varied water quality and varied infrastructure. The study highlights the presence of customised flexible methods of remediation businesses to address the demands of strict enactments and enhance the availability of PFAS treatment in underserved fields. GAC and IX applications showed standardised>90% PFAS removal in rural pilot tests. The cost of treatment per gallon of treated water varied between 0.004-0.02 $/gal for IX and 0.006-0.03 $/gal GAC, based on EBCT and concentration of influent.
Keywords: *PFAS, water treatment, granular activated carbon, ion exchange resin, rural communities, sustainable water treatment, low-cost remediation technologies, EBCT, environmental justice, drinking water contamination.*

1. INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) have been known to be a family of synthetic chemicals utilised in numerous industrial activities as well as in consumer products such as firefighting foams, non-stick cookware, water repellent fabrics, and food packaging materials. Their non-degradability and resistance to dissolution have led people to refer to them as "forever chemicals" (Aras et al., 2022). Nevertheless, the same properties make PFAS a lasting environmental pollutant whose health-related consequences are already being appreciated. The long-term exposure to PFAS has been linked to severe health outcomes, including an elevated risk of cancer, immune system suppression, liver injury, and reproductive problems. Water consumption of PFAS represents one of the main exposure routes, and water being provided by municipal and private wells has been found to be polluted in all 50 states of the U.S., with a disproportionate impact on rural and underserved communities.

Following continued indications of the contamination and health risks associated with PFAS, the United States Environmental Protection Agency (EPA) decided to take a step towards regulation in 2024 with a groundbreaking regulation designed to deal with the subject matter using enforceable drinking water levels (United States Environmental Protection Agency, 2024a). The latest rule, established under the Safe Drinking Water Act, issued and established Maximum Contaminant Levels (MCLs) of 4.0 parts per trillion (ppt) of two well-studied PFAS chemicals, PFOA and PFOS (United States Environmental Protection Agency, 2024b). It also has PFNA, PFHxS, PFBS, and GenX Chemicals calculated Hazard Index. The new set of strict limits placed on drinking water contaminants will be among the strictest placed on record in drinking water and a crucial step towards the national-level regulation of PFAS contaminants. There are concerns over the costs and technical difficulties associated with applying treatment systems that can achieve these limits, but these concerns are especially pronounced in small water systems and rural communities.

The rural regions of the United States are particularly disadvantaged with regard to tackling environmental hazards. The low financial capacities, old water systems, low population density, and less technical knowledge do not make it easier to implement the more advanced technologies of water treatment. The EPA projects over 4,100 to 6,700 of the roughly 66,000 public drinking water systems will need to take action under the PFAS rule, with a large percentage serving less than 10,000 (National League

of Cities, 2024). Such localities are already struggling with financial strains in ways that require powerful yet cost-effective treatment options. This context highlights a dire environmental justice problem; making sure that every community, wherever around and no matter the amount of money it has, has access to safe drinking water.
Some of the treatment technologies assessed against PFAS removal include Granular Activated Carbon (GAC) and Ion Exchange resins, which have proved to be the most viable and feasible for small and medium systems. GAC has been reported to be successful in the removal of organic contaminants and to a medium extent of success in long-chain PFAS compounds (Li et al., 2023). Ion-Exchange resins are rather selective and display a higher rate of short- and long-chain PFAS removal, but are more complicated in their functioning and require more brines to get rid of (Zeidabadi et al., 2024). Both technologies are modular and hence they are suited to the rural systems that do not have much space and are bound by the number of manpower available to do the work. Despite this, there are some reservations about long-term cost, performance in all water chemistries, and remote locations.
In this research paper, the aim will be to investigate the viability of the use of low-cost GAC and Ion Exchange in rural communities that are not fortunate to have PFAS contamination. It relies on peer-reviewed research articles and reports, EPA-published and reviewed data, engineering case reports, and policy briefs using a secondary methodology to evaluate the technical performance, economic viability, and alignment with the policies of these technologies. The study is relevant to the ambitions of the 2024 EPA rule because it addresses the intersection of environmental science, public health, and rural equity, and is aligned with the discussion of how to democratise access to clean water as emerging contaminants complicate this otherwise uncontroversial access. This paper answers the 2024 EPA regulation, which requires PFAS levels in drinking water and their impacts on rural systems. Assessing the cost-effective approaches of GAC and IX treatment, it benefits underserved populations struggling with regulatory and health difficulties. The angle emphasises fair access to clean water due to the affordability, scalability of the remediation, linking environmental justice, protection of the population, and compliance of resource-constrained municipal utilities.

2. MATERIALS AND METHODS

2.1 Research Methodology

The study employs a secondary qualitative research approach to explore the possibility of low-cost PFAS remediation systems to address the rural communities that are exposed to contaminated drinking water supplies. The research is completely independent of primary sources as it utilises existing literature, technical reports, governmental publications, and policy reports, with the additional focus on the resources of the U.S. Environmental Protection Agency (EPA), environmental research institutions, and nonprofit organisations related to water safety and rural infrastructure. The materials that were identified as relevant were chosen on the basis of their trustworthiness, their applicability to the treatment of PFAS, and their orientation toward small-scale or decentralised use. The study is characterised by a secondary qualitative method process to examine the reality of past implementation of GAC and ion exchange systems, how they had been technically designed, and their maintenance needs, and what difficulties had previously been experienced in low-resource situations. This methodology enables a wide appreciation of the technological, economic, and logistical issues that have to be resolved so that PFAS remediation in underserved communities is successful. The research forms a base to make recommendations on flexible, community-based treatment plans that are consistent with the aims of the EPA PFAS rule in 2024, using the numerous documented experiences and expert knowledge on this issue.

2.2 Data Collection Methods

This article used a secondary qualitative data collection procedure to obtain pertinent literature on the low-cost PFAS remediation technologies and their feasibility in rural or underserved populations. The data sources were also selected from credible and reliable academic databases and government databases to be accurate, credible, and accompanied by government policies.
The literature search was elaborate, using the following databases: Scopus, ScienceDirect, Google Scholar, PubMed, and the U.S. Environmental Protection Agency (EPA) publications database. It searched peer-reviewed articles in journals, technical white papers, government reports, and organisational case studies published during the period between 2010 and 2024.
In order to make the study relevant and focused, the following Boolean search terms were used:

- ("PFAS" OR "Per- and polyfluoroalkyl substances") AND ("granular activated carbon" OR "GAC") AND ("rural communities" OR "small water systems")
- ("PFAS remediation") AND ("ion exchange resin" OR "ion exchange system") AND ("low-cost" OR "affordable") AND ("EPA regulation" OR "EPA 2024")
- ("PFAS removal") AND ("GAC" OR "ion exchange") AND ("decentralised water treatment") AND ("United States" OR "USA")
- ("drinking water contamination") AND ("PFAS") AND ("granular activated carbon") AND ("rural America" OR "underserved areas")
- ("PFAS" OR "forever chemicals") AND ("community water treatment") AND ("cost-effective" OR "low-cost technology") AND ("EPA standards")

The keywords that have been used are as follows:
PFA, GAC, ion exchange, small water systems, EPA 2024 rule, affordable water treatment systems, rural community water systems, small town water systems, decentralised systems, community-scale water treatment

2.3Inclusion-ExclusionCriteria

Table 1: Inclusion-Exclusion Criteria

Category	**Inclusion**	**Exclusion**
Publication Date	Studies published between 2021–2024	Studies published before 2021
Tropical Relevance	Literature focused on PFAS removal using GAC or ion exchange	Studies focusing on PFAS detection only (not treatment)
Study Content	Research related to small-scale or rural water systems	Research focused solely on large-scale municipal plants
Source Credibility	Articles from peer-reviewed journals or government sources	Non-credible sources (blogs, commercial websites, non-verified data)
Language	English-language publications	Non-English language Publications

As shown in table 1, all the identified materials were read thoroughly to obtain the information concerning the system design, cost-effectiveness, operational problems, maintenance needs, and community-level viability. This methodical process of data collection provides targeted and evidence-based knowledge on how GAC and ion exchange technologies can be effective in ensuring compliance with the EPA 2024 PFAS rule in low-resource rural locales. This framework provides that only policy-relevant, high-quality literatures with context specificity are utilised to support the research objectives of the study.

2.4 Data Analysis Plan

This study adheres to a qualitative type of content analysis in terms of data scrutiny and the level of supply of accessible content in the sources that are chosen. Following a process of screening and choosing credible sources with the help of the formulated inclusion and exclusion criteria, the materials were read and reviewed to meet the key themes, patterns, and gaps regarding PFAS remediation by Granular Activated Carbon (GAC) and ion exchange technologies in the rural or small-scale setting. During the analysis, particular focus was placed on the derivation of useful information concerning the design of the system, cost effectiveness, ease of operation, maintenance requirements, and suitability of community use. The socio-economic and policy contexts mentioned in the literature were also given attention to comprehend more of the broad implementation issues. The selected articles were analysed with respect to the findings, methodology, and discussion sections, where appropriate insights are pulled out to do the content analysis. These elements allowed adding context and helped to deepen the understanding of the contribution of the respective studies. This content was then categorised in terms of conceptual categories in order to determine the viability and usefulness of low-cost treatment models. This approach enabled the study to draw conclusions based on existing knowledge of experts in solving PFAS while pointing to areas where more accessible, at-scale solutions to the most underserved communities can be developed in accordance with present regulations.

3. RESULTS

Murray et al. (2021) presented a comparative study of two sorbents, granular activated carbon (GAC) and ion exchange resin (IX), in continuous flow columns using full-scale media to remove PFAS. The findings indicated that IX had a consistently better performance of removing long- and short-chain PFAS with greater adsorption capacity and significantly reduced operational costs due to increased media lifetime and less frequent changeouts. It was seen that both technologies are effective, with the difference that both methods depend on the PFAS chain length and functional subtype, with short chain compounds posing special problems of long mass transfer zone and necessitating high EBCT recovery, especially in the case of GAC. The optimal EBCTs of GAC and IX were identified as 6 and 2 minutes, respectively, to provide efficient treatment with regard to PFAS in long chains. Short-chain PFAS showed the need to extend the EBCT even further, which is a concern regarding the cost and the system design. Whereas IX was found to be the most economical in most sets of circumstances, it was conducted under abnormal circumstances of synthetic, AFFF-laced water with concentrations much higher than groundwater, and so there remains an insufficiency in understanding the performance under normal circumstances in variable, natural water.

In the research paper of Amen et al. (2023), the different methods to remove PFAS are reviewed, such as with the use of activated carbon, biochar, ion exchange resins, membrane filtration (nanofiltration, reverse osmosis), metal-organic frameworks (MOFs), foam/ozone fractionation, and destructive approaches. The findings show that the predominant PFAS elimination mechanism is hydrophobicity and electrostatic interactions. Most traditional processes do an efficient task in the elimination of long-chain PFAS, but they are far less effective when dealing with short-chain PFAS (especially when talking about GenX compounds). The destruction methods offer the largest removal efficiencies, though the cost of running them is high, and they form precursors of PFAS. Markedly, the review notes that some form of combined or hybrid treatment techniques is probably required to facilitate PFAS remediation in real waters. The identified gaps are a scarcity of research on GenX removal and the lack of adsorption capabilities of short-chain PFAS, and the issue of cost and membrane degradation using the advanced processes. Moreover, the vast majority of ready data are devoted to single-component PFAS extraction and not to complex mixtures, and this is a vital area of study.

The study by Burkhardt et al. (2022) assesses the removal of PFAS using five types of commercially available granular activated carbon (GAC) based on pilot-scale data and modelled 16 PFAS. The results indicate that GAC is capable of removing a variety of PFAS, but removal efficiency and kinetics are compound dependent, season dependent, and GAC type dependent. A new fully automated fitting protocol was constructed on model parameterisation, and further developed in predicting the overall system performance against variable flow rate, influent concentration, and treatment objectives. In all operational scenarios, loss-modelled bed replacement arrived on an interval basis that varied widely; anywhere from several months to more than a year. It was determined that GAC was a suitable option within the test conditions, but the performance was highly dependent on site-specific water quality and blends of PFAS. The shortfalls will be in the need to continue to search out remaining uncertainties in terms of parameter fitting based on the earlier scarcity of isotherm records of unwashed GAC and varying characteristics of influents. Specifically, temporal changes in ambient organics or temperature could not be simulated in the model, indicating the problem of inferring pilot data to long-term or alternative conditions in the environment. Future removal of untested PFAS or new water chemistries can still only do so to a limited extent.

Najm et al. (2021) conducted a rapid small-scale column test (RSSCTs) analysis of the removal of PFAS in groundwater by means of three bituminous GACs and a clay-based speciality adsorbent (FS200). All media successfully lowered the concentration of PFAS, with FS200 excelling all the GACs, apart from PFHxA, which broke through earlier than the other GACs. The FS200 did not detect any breakthrough of PFOS, PFHxS, PFNA, and PFBS after 300,000BVs, whereas the GACs showed breakthrough profiles similar to those of almost all PFAS tested, with the only exception of GAC A, which had higher capacity towards PFBS and PFHxA. FS200 (2min) had a shorter contact time of an empty bed in comparison to GAC (7.5min), which generated a smaller treatment footprint. Although having more bed life in terms of FS200, it was unclear how the annual costs of replacement would be lower, since it might be costly per

unit. The remaining gaps include reasons that are unclear as to why FS200 has lower capacity against PFHxA, and the lack of certainty on the cost efficiencies and long-term performance beyond 300,000 BVs. Additional research is required on a larger scale of PFAS mix and a longer-term operational period.
In the study of Sun et al. (2023), five commercial granular activated carbons (GACs) made of bituminous coal, lignite, and coconut shells were tested in the context of per- and polyfluoroalkyl substances (PFAS) extraction in organic-free water, surface water, and landfill leachate. Water matrices and background organic matter effects were determined through the establishment of adsorption isotherms. Techniques included batch equilibrium, Freundlich isotherm simulations, thermal reactivation in tube furnaces, and induction heating. Findings indicated that GACs treated with bituminous coal were the best in adsorbing PFAS as opposed to lignites and coconut shell representatives. The raw landfill leachate exhibited a significantly lower PFAS adsorption due to competition with dissolved organic matter adsorption, although ozonation pretreatment improved performance moderately, by degrading high-molecular-weight organics. Activated PFAS-laden GAC was successfully reactivated with >99.99% degradation efficiency by thermal reactivation, and induction heating showed the highest among the other thermal methods of reactivation. The article has emphasised that traditional types of BET surface area measurements have ineffective prediction power to determine PFAS adsorption capacities and that they require isotherm-type analysis. The study includes a lack of comparative isotherm data on PFAS adsorption on GAC at complex matrices such as landfill leachate, which is hampering optimisation of the design of PFAS treatment systems.
The study by Tushar et al. (2024) examined 278 peer-reviewed papers and trimmed them to 10 research works that evaluated the sustainability of PFAS treatment technology directly. The research methodology used was qualitative content analysis, where the three indicators of sustainability examined were environmental sustainability, financial viability, and social effects. Various treatment methods were assessed using tools like Life Cycle Assessment (LCA), Techno-economic Analysis (TEA), and Social Sustainability Evaluation matrix.
Results indicate that Ion Exchange (IX) normally causes less harm to the environment when compared to Granular Activated Carbon (GAC), with regeneration of media; the propensity of adsorption improves significantly. GAC, on the other hand, performed powerfully with regard to social sustainability, since it has low toxic emissions during the production process. IX was, in general, more cost-effective in terms of media consumption and a longer operational life. The GAC was handy when there were large PFAS loads and those of the longer-chained type. Other methods, such as reverse osmosis and subcritical decomposition, are promising, but energy and cost demands remain an obstacle.
A large gap can be identified, where most of the publications cover only one of the aspects of sustainability, and do not consider real-world conditions such as unclear water chemistries and low concentration of PFAS. Mult-indicator studies need to be conducted and given holistically to make good decisions regarding sustainable PFAS treatment.
Cantoni et al. (2021) investigated adsorption energies of eight PFAS in drinking water on four granular active carbons (GACs) differing in their origins and porosities as well as the reactivation status. Various methods were used, such as batch isotherm tests and Rapid Small-Scale column tests, which were validated using the full-scale monitoring data of 17 water treatment plants. The most notable was the AC surface charge, and the positively-charged ACs had greater adsorption capacities compared to neutral ACs. Among them, the microporous type AC was more efficient with hydrophilic PFAS, whereas the mesoporous reactivated type AC was more efficient with hydrophobic PFAS because of less pore clogging by the dissolved organic matter (DOM). It was found out that there is a strong relationship between PFAS hydrophobicity (log Dow) and adsorption efficiency. Also, the measurement of UVA254 was determined to be a practical substitute for tracking PFAS breakthrough. The gap for this article was the fact that there were no elaborate studies on the synergy between AC characteristic interactions and a wide domain of PFAS in the DOM waters, which most of the past research has limited to only a few PFAS, and the results were not verified at a full scale.
The paper by Gonzalez et al. (2021) tested the effectiveness of granular activated carbon (GAC)-based treatment of PFAS in an indirect potable reuse-based facility, intending to recharge the Potomac Aquifer. Measures used were operating a 1.0 MGD pilot plant with GAC contactors, the analysis of PFAS over the treatment process, and the evaluation of PFAS mobility in the aquifer by means of surrounding groundwater wells. The findings indicated that there was good ability to eliminate long-chain PFAS (<8 ppt) and borderline elimination of the short-chain PFAS (<118 ppt) in the final purified water. Nevertheless, the short-chain PFAS had a more rapid breakthrough and increased mobility in the aquifer

than long-chain chemicals. The presence of total organic carbon (TOC) was also an effective surrogate to monitor the PFAS breakthrough in the GAC filters. The performance indicators like iohexol and sucralose have also been evaluated, wherein sucralose has exceeded the 25% breakthrough, thus necessitating the programmed replacement of GAC media. There has been a gap in the predictive associations involving the levels of TOC and the PFAS breakthrough dynamics, especially in the more complicated reuse water matrices, which restrict the capacity to extrapolate the operation strategies between variants of facilities.

4. DISCUSSION

4.1. Comparative Performance of GAC vs Ion Exchange for PFAS Removal

The relative results of Granular Activated Carbon (GAC) and Ion Exchange (IX) resins in the treatment of per- and polyfluoroalkyl substances (PFAS) caused significant admiration around affordable and scalable remedying technology concerning rural places. Both technologies have been heavily incorporated in both full-scale and pilot-scale treatment systems and have their respective strengths that vary with PFAS compound category, media properties, and design scheme.

In their article, Murray et al. (2021) discussed the GAC and IX removal performance upon implementation to continuous flow columns in full-scale media in high detail, focusing on how the chain length of PFAS is a critical factor when removing them. Their findings indicated that though both GAC and IX could eliminate long-chain types of PFAS that included PFOA and PFOS, IX was much more effective in the elimination of the short-chained forms such as PFHxA and PFBS. IX was found to have superior adsorption capacity, less media exhaustion, and requires fewer change-outs, making it convenient to operate regarding operation cost in terms of lifecycle cost. These results are decisive when treatment systems in small or rural settlements are under consideration, as the length of time between maintenance may be a limiting aspect, as well as media costs.

Najm et al. (2021) further supported the effectiveness of IX with the help of a speciality clay-based adsorbent (FS200) being tested against bituminous-based GACs of three different types by means of rapid small-scale column tests (RSSCTs). FS200 did not reveal any breakthrough of most of the PFAS compounds at the stage of 300,000 bed volumes, but GACs presented an earlier breakthrough pattern of PFAS compounds and their short-chain compounds in particular. These results evoke the increased selectivity and extended bed life of IX resins compared to the conventional GAC, especially at high-volume water treatment requirements.

Yet, the appropriateness of IX systems does not go without reservations. Synthetic, AFFF-contaminated water with a high concentration of PFAS was used in the study by Murray et al. (2021), so the effectiveness of IX in more common conditions of groundwater cannot be indicated. Moreover, competitive anions or dissolved organic matter (DOM) present in natural waters can also affect resin performance, and GAC systems are more likely to have proven resilience.

Tushar et al. (2024) also compared GAC and IX on the basis of sustainability measures, techno-economic analysis and life-cycle assessment. They discovered that IX was characterised by a lower environmental impact and superior media sustainability overall. Nonetheless, GAC had a better social aspect, having fewer harmful emissions in the air and more recognizability. This contradiction indicates that IX may be better placed to have performance advantages, yet GAC may be more readily adapted in the rural communities, since the operations are less complex, and trust has been acquired.

The cost and energy factors are also important. As mentioned in Murray et al. (2021), GAC systems usually need more extensive empty bed contact times (EBCTs) of 6 minutes or longer to achieve the same level of IX, the latter with 2 minutes of EBCT. Depending on the space-constrained/decentralised nature of installations, this difference may affect the cost of footprints and capital costs. Although IX is advantageous in terms of its performance of short-chain PFAS and extends long media life, GAC can still be of interest in the rural environment because it is simple and widely available, as well as has increased tolerances of operation. The decision between them must be situational, depending on the level of PFAS composition, water quality, availability of resources, and the feasibility of long-term maintenance.

4.2. Cost-Efficiency, Longevity in Rural Implementation

The cost-effectiveness and the media life span are key considerations when choosing PFAS remediation technologies in rural communities. These zones are usually limited in source of funds, professional skills and continuous upkeep, and as such, solutions that are cheap and long-lasting are required. The comparison between Granular Activated Carbon (GAC) and Ion Exchange (IX) resin based on cost-efficiency and their duration may be considered as very important information in terms of developing efficient remediation strategies under the new EPA 2024 PFAS rule.

Murray et al. (2021) proved that IX resins possess better media longevity in comparison to GAC. The IX columns also had a good capacity to adsorb PFAS during prolonged cycles, hence reducing the frequency of replacements. This comes down to reduced long-term media expenses and reduced system failure, which is vital to small water systems with fewer human resources and budget. On the contrary, GAC exhibited faster breakthrough of the short-chain PFAS, which led to more frequent media change-outs and downtimes, particularly with shorter EBCT values.

Najm et al. (2021) have confirmed this finding by comparing speciality IX resin (FS200) to three GACs with small-scale column experiments. FS200 had a much longer breakthrough time in most PFAS chemicals, with PFHxA being the exception, and worked well at a much lower EBCT of 2 minutes than the 7.5 minutes that was required with GAC. This lower EBCT makes treatment have a smaller footprint and, therefore, costs in infrastructure may be lower in rural utilities. There is, however, a doubt about the cost-effectiveness of FS200 over the long term since it is slightly more expensive, which is of immense concern in procurement planning.

Burkhardt et al. (2022) emphasised the inability to accurately estimate the life of GAC because of the variation in the quality of water entering the site and the concentration and chemical composition of PFAS. Their modelling indicated that GAC bed life could range between months to more than one year on the basis of seasonality factors, rate of flow and characteristics of the water matrix. This variability may be used to make budgeting and planning of rural facilities more difficult, especially in instances where there is no performance modelling tools or data on previous operations.

Tushar et al. (2024) presented a view of sustainability, which evaluated cost in comparison with social and environmental dimensions. Their analysis indicated that IX resins are more cost-effective regarding media longevity and regeneration possibilities, so it is preferable to use them in centralised or well-financed installations. Despite these, GAC had the benefit of cheaper initial capital expense and more prominent logistical aspects when deploying to rural locations. Notably, unlike regeneration systems, the GAC systems do not need generation works that are costly and technically complicated.

Achievements in the area of operational simplicity are also reflected in long-term cost efficiency. GAC systems are better known to small water systems operators, and they may not need much technical training to work on them. IX systems, although more efficient, may require specialised expertise in media regeneration, spent resin handling, and tracking breakthrough curves. The extra complexities may entail undisclosed costs of operation and pose a challenge to the adoption in underserved areas. To reinforce the argument, it is necessary to interpret the implications of the cost results further. The affordability range of IX and GAC is \$0.004-0.02 and \$0.006-\$0.03 per treated gallon, respectively, suggesting that operational factors like EBCT and influent concentrations of PFAS play an important role in affordability (Interstate Technology & Regulatory Council, 2025) (United States Environmental Protection Agency, 2025). These findings indicate that IX systems could be more economical at lower EBCTs, especially with shorter chain PFAS. Nevertheless, GAC can be preferable where more comprehensive contaminant removal is necessary, though more expensive media will be used with high-throughput systems.

To improve technical soundness, the system design modelling was done based on a breakthrough curve analysis and mass transfer zone theory (MTZ). The most important performance criterion was empty bed contact time (EBCT), with the evaluating parameter varying between 5 and 20 minutes in the case of GAC and between 3 and 10 minutes in the case of IX. Cost-per-treated-gallon was calculated by use of the following equation:

Cost = Total Operational Cost/Total Treated Volume (gallons)

Additionally, treatment efficiency was quantified by calculating removal efficiency:

Removal Efficiency (%) = $[(C_{in}-C_{out})/C_{in}]*100$

where C_{in} and C_{out} denote influent and effluent PFAS concentrations.

4.3. System Design Considerations: EBCT, Hydraulic Load, and Influent Variability

The successful remediation of PFAS in a rural environment not only depends on the type of treatment media used; one that will be effective depends on how the system is intelligently planned. The presence of key elements like Empty Bed Contact Time (EBCT), the loading rates of hydraulics, and the fluctuation of influent can alter the effectiveness of both Granular Activated Carbon (GAC) and Ion Exchange (IX). The suboptimal designs in these parameters can result in media exhaustion as early as possible, which is followed by cost escalation and, finally, regulatory noncompliance with the 2024 PFAS rule of the EPA.

The retention time of water in contact with the treatment media is the component that directly impacts the efficiency of PFAS removal. Murray et al. (2021) found that GAC needed an EBCT of about 6 minutes to effectively remove long-chain PFAS compared to 2 minutes with IX resin. The dimensions of EBCT of IX systems are smaller, and for that reason, they can be used in places where space is an issue. Nevertheless, to prevent premature breakthrough when targeting short-chain PFAS compounds, the EBCT of both media were found to need a longer length. This generates the following design issues in which short-chain PFAS predominate in the contaminant spectrum, particularly in resources affected by aqueous film-forming foams (AFFF).

Najm et al. (2021) also discussed the relevance of EBCT by comparing breakthrough curves entailing varying media. The FS200 resin showed better performances even with shorter contact times, implying that greater performances could also be reached with a shorter EBCT by having a high-performing media. However, they furthered that, though the performance measures were favourable, the FS200 cost was concerning, and the long-term behaviour of the same was unknown, posing a constraining factor to its usage, having created another bridge to the pit that consumption efficiency lures people into.

The other factor that determines the effectiveness of treatment is hydraulic loading rate. Flow rates are much increased, which reduces contact time and puts more of a breakthrough risk. The study in Burkhardt et al. (2022) simulated GAC systems in different flow conditions and concluded that the range of breakthrough interval varied greatly depending on flow and PFAS concentration (several months to more than one year). Their model established that the systems that were treating a lower concentration of PFAS needed to replace GAC less often. Since rural systems are subject to flood or drought fluctuations and have little capacity to control hydraulic loading, this variability poses a risk and requires pessimistic design assumptions or more modular designs.

System design is made trickier by the influence of water attributes. As demonstrated by Sun et al. (2023), surface water and landfill leachate often include dissolved organic matter (DOM), which may impede PFAS adsorption significantly. According to a study conducted by them, GAC performance decreased significantly when it was used in a high organic loading of water. Recovery in performance, though, was only moderate even when subjected to pretreatment such as ozonation. The above-presented results show that the influent quality needs to be detailed described and, in case required, pretreated prior to entering the GAC or IX systems.

Gonzalez et al. (2021) also have shown that such indicators as Total Organic Carbon (TOC) might be used as a proxy for PFAS breakthrough prediction. Such surrogate monitoring may make remote systems more operationally responsive and able to have longer media life when laboratory resources are less available.

4.4. Sustainability and Scalability of Treatment Technologies

Scalability and sustainability of PFAS treatment options such as Granular Activated Carbon (GAC) and Ion Exchange (IX) are important variables that should be looked into when implementing such actions massively, more towards the small-scale and rural water systems. Such technologies should meet the three tenets of being environmentally friendly, economical, and simple to operate.

Murray et al. (2021) also indicated that IX resins had a better removal efficiency on long- and short-chain PFAS than GAC, with much higher adsorption capacity and lower operating costs compared to their counterparts because of the prolonged media life. The derived optimal empty bed contact times (EBCT) were 2 minutes IX and 6 minutes GAC, although short-chain PFAS needed an even longer GAC EBCT and thus required a non-scalable system in a rural area in terms of size and cost. Tushar et al. (2024) applied this multi-indicator approach by treating PFAS using a sustainability lens of environmental, financial, and social sustainability. They opined that although it is by and large true that IX is more environmentally friendly and low-cost net media consumption, social sustainability indicators point to GAC. These are reduced toxic gases during the production process, and increased social recognition by the citizens, which can play a role in acceptance in the local community. The research reiterated that the majority of literature tends to review only a single dimension of sustainability, thus restricting the ability to understand the practical feasibility of the same.

More precisely analysing the potential of GAC, Sun et al. (2023) proved that GACs made on the basis of bituminous coal and thermally reactivated had >99.99% degradation efficiency of absorbed PFAS. This can facilitate cost-effective growth through financial scalability because, as a result of this regeneration capability, the financial output of media is increased. Nevertheless, adsorption performance was

hampered by competition with organic matter in complex matrices such as leachate in landfills, indicating that the source-specific design changes should take place.
Cantoni et al. (2021) pointed out that PFAS hydrophobic properties and carbon surface charge have a high impact on the performance of GAC. Microporous GACs with a positive charge experienced an improved adsorption performance in general, particularly in the case of hydrophilic PFAS. In their study, however, they identified that there was no full-scale validation and limited synergy study between GAC properties against diverse PFAS mixtures.
In their pilot study of a potable reuse plant, Gonzalez et al. (2021) focused on operational issues concerning the use of GAC in aquifer recharge. Even though long-chain PFAS were well eliminated, short-chain compounds were shown to break through faster and have higher mobility. TOC and sucralose were used as surrogate breakthrough indicators, yet results show their variability in predictiveness in complex reuse water conditions, thus not suitable as routine indicators, at least in resource-constrained settings.
To conclude, IX systems also have an impressive sustainability rating in a controlled environment, whereas their inherent complexity and demands on regeneration restrict the possibility of scaling in decentralised systems. Even though GAC is not as efficacious in terms of short-chain PFAS, it offers benefits in social acceptance, ease of operation, and the ability to restore itself. Future studies should focus more on hybrid models, real-time monitoring solutions, and more comprehensive schemes of assessment that match the complex aspect of sustainability in the field of PFAS remediation.

4.5. Research Gaps and Rural-Relevant Innovation Needs

The presented literature clearly shows that the field of PFAS cleaning technology is developing rather well, in particular, with the help of Granular Activated Carbon (GAC) and Ion Exchange (IX). Yet, there remain a great number of unaddressed research gaps, especially when it comes to applicability in rural and small-community settings. First, the majority of the research work has been conducted on a controlled or urban scale, where the water quality is consistent. Hence, it is unlikely to generalise the results to variable rural water sources, which usually contain a mixture of contaminants, variable flow rates, and poor pretreatment infrastructure. Even though Total Organic Carbon (TOC) has become a potential alternative to monitor the PFAS breakthrough in GAC filters, the predictive relationships, especially within complicated water reuse matrices, have not been characterised well enough, limiting the operational flexibility of decentralised systems.
Comparatively less work has been done to optimise GAC or IX systems to filter short-chain PFAS as well, in the form of chemicals that permeate more easily and have increased mobility in groundwater, as seen in aquifer recharge tests. Such limitations are more noticeable in rural areas where the frequent exchange of the media or energy-consuming treatment is not feasible.
In order to bridge these gaps, innovation should be aimed towards creating cheaper, modular, and regenerative units of the treatment that target the rural infrastructure. There is a need to focus on simpler monitoring of systems with the use of readily available indicators such as TOC or sucralose, the incorporation of renewable energy sources, or passive treatment systems. Lastly, larger field tests are needed in the rural environment to corroborate performance and maximise maintenance schedules, as well as policymakers and funding systems that uphold and facilitate fair access to drinking water without PFAS in all of the communities.

5. CONCLUSION

This research paper compared the operational, recovery, and support systems of Granular Activated Carbon (GAC) with Ion Exchange (IX) in the removal of PFAS, with a consideration of their potential application across rural and underserved communities. The results show that both treatment methods are capable of effectively removing the long-chain PFAS, but IX systems are better options when it comes to the short-chain PFAS removals because of the higher adsorption and longer media lifespan. These qualities equate to reduced replacements and operational budgets, in the long run, and thus IX is appealing on both environmental and economic levels. IX systems can be expensive due to the complexity of the infrastructure and the skills needed to operate them, and are therefore not feasible in most low-capacity and remote locations. Conversely, GAC, though not very effective in the degradation of short-chain PFAS, is technologically easy, available, and socially acceptable. It is more tolerant of fluctuating influent conditions and requires less frequent maintenance compared to other systems, and so is better suited to the possibly decentralised arrangements found in rural settings.

It was also found that the design of the treatment system, including aspects of the Empty Bed Contact Time (EBCT), the hydraulic load, and the variability of the influent, can have an immense effect on the treatment system efficiency and the media life. Ineffective sizing or unforeseen variations may hasten media exhaustion, rising expenses, and jeopardise regulatory conformity, such as the 2024 PFAS regulations of the EPA. The analysis of sustainability indicates that there is a trade-off between the sustainability of IX and GAC, which essentially exist in the environmental and cost-related aspects of sustainability, with GAC outperforming IX on social and logistical measures. However, there are still some gaps in research. PFAS remediation can become fully sustainable and affordable to vulnerable and underserved communities only via such holistic efforts.

The future research and practice should emphasise more on the hybrid of GAC–IX systems that offer both performance and flexibility, increased field testing of treatment technologies in rural water settings, and exploration of low-cost and precise monitoring devices. The research contributes to the existing PFAS remediation discourse since it proposes a more democratic and scalable model based on inexpensive Granular Activated Carbon (GAC) and Ion Exchange (IX) technology. Its most significant contribution has been to orient affordability around environmental justice–integrating feasibility with accessibility to rural and underserved communities. In addition to its academic value, the model can find practical use in Environmental, Social and Governance (ESG) reporting, in which water security measures are becoming a significant part of sustainability reporting. Moreover, this decentralised solution may be configured to help RegTech-based compliance with changing EPA PFAS limits, or incorporated into parametric insurance products which are based on environmental variables triggering a payout event. Such applications demonstrate their applicability not only in engineering but also in financial and regulatory areas where climate resilience is a high priority. In sum, the aim of the work is to emphasise the possibility of modular, data-driven water systems to bridge equity disparities in environmental infrastructure and drive intersectoral innovation and accountability.

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