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Spent Media Management Pathways for PFAS Treatment Applications

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ABSTRACT

Removing PFAS from water is increasingly needed to comply with evolving regulations in multiple industries, including drinking water production, municipal and industrial wastewater treatment, and contaminated site remediation. This change is driving increased use of adsorptive media to remove PFAS from drinking water. Granular activated carbon (GAC) and anion exchange resin (AER) are the two predominantly applied media used to separate PFAS from water. Both technologies produce PFAS-laden spent media that requires downstream management, with significant operating costs and regulatory uncertainty. Once GAC or AER media is spent, it can be physically changed out from treatment vessels or regenerated in place. Spent media can be managed through existing offerings like incineration or GAC reactivation or through emerging offerings like supercritical water oxidation (SCWO). Spent regenerant can be recovered and reused, with concentrated PFAS-laden liquid managed through offsite incineration or emerging PFAS destruction methods. Both offsite GAC reactivation and onsite regeneration of either AER or GAC have the potential to reduce operating costs and energy use relative to single-use media procurement and disposal.

1 | Introduction

PFAS are a diverse group of persistent, anthropogenic chemicals that are increasingly regulated in products, waste management, environmental media, and drinking water (Evich et al. 2022; OECD 2025). The chemical strength of carbon–fluorine bonds makes PFAS useful for their water and grease resistance, durability, and low friction (ECHA 2023) but also contributes to their persistence, which many argue is sufficient reason for environmental regulation to limit future, irreversible exceedance of known and unknown health risks (Cousins et al. 2020). Chemical persistence and mobility also make PFAS difficult and expensive to remove from environmental media, costing millions of dollars per kilogram of PFAS removed and destroyed using technologies currently available at large scale (Ling 2024).

The regulatory landscape for managing PFAS in the water and wastewater treatment sectors is evolving. For drinking water, the US EPA has established maximum contaminant levels (MCLs) for six PFAS (40 CFR Part 131 Subpart B—Establishment of Water Quality Standards 2024). The final rule has designated reverse osmosis (RO) or nanofiltration (NF) membrane separation, GAC, or AER as best available technologies. However, RO

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Summary

- PFAS-laden spent media requires downstream management, with significant operating costs, regulatory uncertainty, and ongoing technology development.
- Media management pathways should be evaluated early in a project and incorporated into treatment system design.
- Virgin media production is the largest contributor to life-cycle costs and energy.
- Media regeneration or reactivation can lower costs, depending on capital equipment needs, and is established in industrial wastewater treatment.
- Use of regenerated and reactivated media in potable water applications is currently limited by regulatory requirements in some regions.

and NF for drinking water treatment are effectively limited to coastal areas due to the high costs of brine disposal in inland applications. Despite rapid advancement in an array of PFAS separation and destruction technologies, GAC and AER remain industry standards for separating PFAS from water due to high achievable effluent water quality and volume concentration (i.e., ratio between water volume treated and volume of residuals produced) (US EPA 2024a). Thus, GAC and AER are likely to be the most widely applied PFAS separation technologies for drinking water systems working to meet the 2029 MCL compliance deadline. Because these media need to be regenerated or changed out to maintain PFAS separation efficacy, the volume of spent GAC and AER requiring management will also increase.

On the wastewater side, removal and destruction of PFAS from municipal water resource recovery facility (WRRF) effluent could drive up household wastewater rates by a factor of 2–200 (Ling et al. 2024). The extreme unaffordability of PFAS treatment at municipal WRRFs highlights the need to focus on source reduction and industrial pretreatment as the primary means of limiting PFAS emissions through WRRFs. The US EPA has stated that it intends to use the NPDES program to reduce PFAS in industrial wastewater discharges (US EPA 2021, 2022), and updated Effluent Limitations Guidelines support restriction of PFAS in industrial wastewater discharges. In response, many municipal WRRFs are evaluating and limiting upstream sources of PFAS (NACWA 2024). Increased PFAS treatment for industrial wastewater discharges could further increase demand for spent media management.

For this article, we define spent media as adsorbents, such as GAC or AER, that have been used in PFAS separation processes and have reached their design bed life. Currently, targeted guidance for how facilities can manage spent media like GAC and AER is limited. Recent US EPA guidance for disposal and destruction of PFAS-laden wastes lists only landfilling, high-temperature incineration, and deep-well injection as approved methods. Other technologies are "neither encouraged nor discouraged." Consistent with this guidance, most PFAS-laden, spent media is currently disposed in a landfill or treated using reactivation (for GAC) or high-temperature incineration (US EPA 2024b). Landfilling does not destroy PFAS, serving instead as a short- to or medium-term sink and potential future source of PFAS (Evich et al. 2022; Lin et al. 2024). Conversely, high-temperature incineration faces regulatory uncertainty (Illinois State Legislature 2022; New orkY State Legislature 2020; US Department of Defense 2023) and limited capacity (US EPA 2024c). Due to the high stability of carbon–fluorine bonds, mineralization of PFAS to non-PFAS endpoints is energy-intensive and can be difficult to verify (Shields et al. 2023; Smith et al. 2024). Direct thermal treatment via incineration can require temperatures at or above 1000°C for broad-spectrum PFAS mineralization, although lower temperatures may suffice under specific operating parameters (Winchell et al. 2021, 2024).

This work summarizes the status and outlook for spent GAC and AER management pathways, including the technology readiness level and PFAS fate for technologies considered. Estimated energy use and operations and maintenance (O&M) costs per dry mass of spent media are also presented. With increasing implementation of PFAS removal in water and industrial wastewater systems, this information will support planning and decision making for existing and future treatment systems.

2 | Methods

2.1 | Review of Technologies and Assembly of Spent Media Management Pathways

Complete pathways include two key steps: removing PFAS from treatment vessels via changeout or regeneration and managing PFAS-laden residuals. Established and emerging technologies used for spent media management were reviewed, evaluated, and assembled into potential pathways. Spent media management technologies were assigned technology readiness levels (TRL) based on established US Department of Energy guidelines (US DOE 2011). TRL values between 0 and 5 reflect increasing levels of conceptual to bench-scale demonstrations, while TRL 6 through 8 reflect increasing levels of pilot to full-scale demonstration. A TRL of 9 reflects technologies that are commercially available and demonstrated across the full range of expected conditions.

The ultimate fate of PFAS in spent media management is another differentiating factor and is complicated by the fact that PFAS transformation into other PFAS is not always reported by technology performance studies that measure a set number of "targeted" PFAS (Smith et al. 2024). PFAS fate is categorized here using four different destruction fate levels:

- Fate 0 = PFAS reenters environment soon after disposal—this includes RO brines routed to surface water without a PFAS destruction step.
- Fate 1 = PFAS are not destroyed but is sequestered for a period of time ranging from years to centuries—this includes landfilling and deep-well injection disposal.
- Fate 2 = Some PFAS are destroyed, with an unknown amount returning to environment. This includes some incineration processes not achieving complete PFAS destruction.

TABLE 1 | Technology readiness and PFAS fate for spent media management technologies in industrial wastewater applications.

	Technology	TRL[a]	Spent media and PFAS fate
Removing PFAS from tanks	Media changeout	9	Media with PFAS physically removed and managed offsite
	Onsite AER regeneration	9	Media regenerated in place, PFAS to concentrated liquid
	Onsite GAC regeneration	4–5	Media regenerated in place, PFAS to concentrated liquid
	Emerging onsite regeneration technologies (not evaluated in detail)	2–3	Media regenerated in place, PFAS to concentrated liquid
	Technology	TRL[a]	Final PFAS fate and routing
Managing PFAS residuals	Landfilling (not evaluated in detail)	9	Sequestered in landfill, released in gas and leachate (Fate 0–1)
	High-temperature incineration	9	Partial to near-full destruction in incinerator (Fate 2–3)
	GAC thermal reactivation	9	Partial to near-full destruction in thermal oxidizer (Fate 2–3)
	Solid-phase SCWO	7	Near-full destruction in SCWO unit (Fate 2–3)
	Liquid-phase destruction (HALT, SCWO, Plasma, ARPs, ECO)	3–7	Near-full destruction (Fate 2–3)

[a]Technology readiness level (TRL) based on US DOE guidance and definitions (US DOE 2011). TRLs for specific media management options were assigned based on available literature and commercial availability status.

- Fate 3 = Full PFAS mineralization is likely—this includes incineration processes achieving near-complete PFAS destruction and GAC reactivation, supercritical water oxidation (SCWO), electrochemical oxidation (ECO), nonthermal plasma, hydrothermal alkaline treatment (HALT), and advanced reduction processes (ARPs).

Table 1 lists established and developing technologies for PFAS-laden spent media management, including the initial TRLs and PFAS fate as categorized above. Detailed evaluation and combination of these technologies is discussed in subsequent sections.

2.2 | Basis for Energy Use and O&M Cost Estimates

Established technologies with TRLs over 5 and including PFAS destruction (fate level of 2 or 3) were assembled into complete media management pathways for further consideration. Energy use and operation and maintenance (O&M) costs were estimated per dry mass of spent media requiring management across the full media life cycle, including virgin media production and residuals management. Media mass was chosen as a functional unit over volume of water treated because it carries fewer inherent assumptions regarding water quality, system design, treatment targets, permit conditions, and other factors that affect media use rates. Site-specific treatment cost estimates for any facility can be developed by multiplying cost or energy per dry mass by the site-specific media usage rate per volume of water treated.

Unit costs and operating assumptions used to develop energy use and costs per dry mass of spent media are outlined in Table 2. Generally, energy use and costs for emerging technologies were sourced from vendor estimates, while data for existing technologies were based on literature or SimaPro modeling described below. For onsite media regeneration, energy use includes electricity and natural gas equivalent energy use onsite, plus chemical use for regenerants and destruction technologies. Energy use for residuals management includes transport to disposal facility and use of electricity, natural gas, and chemicals. O&M costs include procurement and delivery of replacement media, changeout or regeneration, residuals transport, and final disposal. The O&M costs presented reflect costs to water treatment facilities, not to disposal facilities. More detailed energy use and cost calculation breakdown and rationale are included in Tables S1 and S2.

SimaPro models (PRé Sustainability; Amersfoort, NL) were developed to estimate energy use for established adsorbent media production and disposal technologies using life cycle assessment (LCA) methodologies consistent with ISO standard 14040:2006. Inventory items relevant to production of virgin adsorbent media, thermal GAC reactivation, and high-temperature incineration of spent media were all obtained from the ecoinvent 3.1 database, with specific inventory items listed in Table S4. These inventory items were modeled as unit processes using the Cumulative Energy Demand v1.10 impact assessment method developed by PRé Sustainability (Frischknecht et al. 2015). Inventory item models were normalized per dry mass of media production/disposal and include materials extraction, synthesis steps, electricity and thermal inputs, and energy recovery in the cumulative energy models. Process flow models detailing the major sources of energy consumption are shown in Figures S3–S7, with overall energy values generally agreeing with those found in literature (Barr Engineering Co. and Hazen and Sawyer 2023; US EPAUS EPAUS EPAUS EPAUS EPA 2024b; Vilén et al. 2022).

TABLE 2 | Basis for energy use and O&M cost estimates, per mass dry spent media.

Item	Unit/cost range used	Sources
Water content of spent media	50%	Based on author experience
Transport distance to offsite disposal facilities	340 km (200 miles)	Assuming regional network of facilities is established
Transport costs	$1.9/km ($3/mile) per 40-ton truck	(DAT Freight and Analytics 2024)
Energy use for virgin GAC virgin media production, including coal	29–33 kWh/kg (13–15 kWh/lb)	(Vilén et al. 2022) and SimaPro modeling documented in SI
Energy use for virgin AER virgin media production	18–24 kWh/kg (5–11 kWh/lb)	(Battelle, forthcoming) and SimaPro modeling documented in SI
Energy use for onsite regeneration	4.4 kWh/kg AER regenerated 2.4 kWh/kg GAC regenerated	From ECT2 and Revive Environmental
Energy use for thermal GAC reactivation	1.8–3.3 kWh/kg (0.8–1.5 kWh/lb)	(Vilén et al. 2022) and SimaPro modeling documented in SI
Virgin media makeup for thermal GAC reactivation	15%–30% of media sent to reactivation	(Redding 2024; US EPA 2024c)
Energy use for incineration (varies depending on degree of energy recovery)	3.1–7.5 kWh/kg (1.4–3.2 kWh/lb)	(Barr Engineering Co. Hazen and Sawyer 2023) and SimaPro modeling documented in SI
Energy use for SCWO destruction	0.04 kWh/kg GAC or AER destroyed via SCWO	From 374Water
GAC media cost	$4.4–$7.7/kg ($2.0–$3.5/lb)	(Barr Engineering Co. Hazen and Sawyer 2023; Murray et al. 2021; US EPA 2024b)
AER media cost	$18–$33/kg ($8–$20/lb)	(Barr Engineering Co. Hazen and Sawyer 2023; Murray et al. 2021)
Onsite regeneration costs	$0.26–$0.40/kg AER regenerated $2.6–$4.0/kg GAC regenerated	From vendors Revive Environmental and 374Water
O&M costs for liquid destruction of regeneration residuals	$0.13–$0.66/kg media regenerated	From vendors Aquagga and Revive Environmental
Thermal reactivation fees	$2.0–$2.9/kg ($0.9–$1.3/lb media)	Estimated from (US EPA 2024b)
High-temperature incineration tipping fees	$2.2–$3.3/kg ($1.0–$1.5/lb media)	(US EPA 2024b)
O&M costs for SCWO destruction	$0.44/kg GAC or AER destroyed via SCWO	From 374Water

Further technical information can be found in the Supporting Information and the ecoinvent v3.1 dataset documentation (ecoQuery 2024; Wernet et al. 2016).

Capital costs were not included, because they are more affected by economy of scale, such that total capital costs per media capacity or changeout will vary significantly between sites for a single technology. Additionally, capital costs per mass of media (the functional unit adopted in this study) will scale based on media use rate, which may vary by multiple orders of magnitude between systems. These and other capital costs were not included in this cost analysis but should be evaluated and included in site specific cost evaluations developed for planning purposes.

3 | Detailed Evaluation of Spent Media Management Pathways

3.1 | Technologies to Remove PFAS From Treatment Vessels

3.1.1 | Media Changeout for Offsite Management (TRL = 9)

Physically removing and replacing media from vessels (i.e., "media changeout") has a TRL of 9 and is commonly used for spent media management pathways with offsite spent media management. The process typically involves the GAC

vendor providing transfer hoses and a truck with compartments for both spent and replacement GAC (DESOTEC 2025; Redding 2024). A water supply is required for this activity and used with a designated pump to slurry the media out of treatment vessels and into trucks for transport. Once a facility has determined a media changeout is approaching or otherwise required, media changeout requires weeks to months of planning and coordination between the facility and involved third parties. Specific planning and coordination activities can include the following:

- contracting with third parties
- characterizing spent media
- preparing the facility and equipment for media changeout
- hauling virgin or reactivated media from source to treatment facility
- executing and coordinating changeout, including loading replacement media
- hauling spent media from treatment facility to disposal facility
- preparing replacement media for use
- collecting any required samples after vessel preparation
- providing onsite coordination and documentation of the event

3.1.2 | Onsite Regenerable IX (TRL = 9)

Regenerable IX (IXR) systems are a potentially more sustainable and cost-efficient alternative to single-use operation of IX systems (Ellis et al. 2025). PFAS can be removed from strong base AER through in-place, onsite regeneration using a brine and solvent solution. Using parallel treatment trains and/or lead/lag vessels can enable uninterrupted treatment during regeneration events. While many single-use resins have been found to be regenerable in the short-term (Ellis et al. 2025), regeneration is likely most cost-effective and efficient when using specialized IXR media (Dixit et al. 2021), suggesting IXR consideration should occur before the media purchasing phase. IXR vessels also require some modifications (e.g., tank linings and valve configurations) compared to single-use IX vessels.

Figure 1 illustrates an IXR process with PFAS destruction of still bottoms. In some cases, regeneration may be required more frequently than single-use IX changeout due to slightly lower PFAS capacity of IXR (Boyer et al. 2021; Ellis et al. 2022). The spent regenerant contains a mixture of the desorbed PFAS and other desorbed constituents such as natural organic matter (NOM), nitrate, organic solvent, water, and salts (Kempisty et al. 2024; Woodard et al. 2017). Spent regenerant is distilled to capture and reuse the solvent fraction in subsequent regeneration cycles. The resulting, aqueous still bottoms contain highly concentrated PFAS, salt, and organics

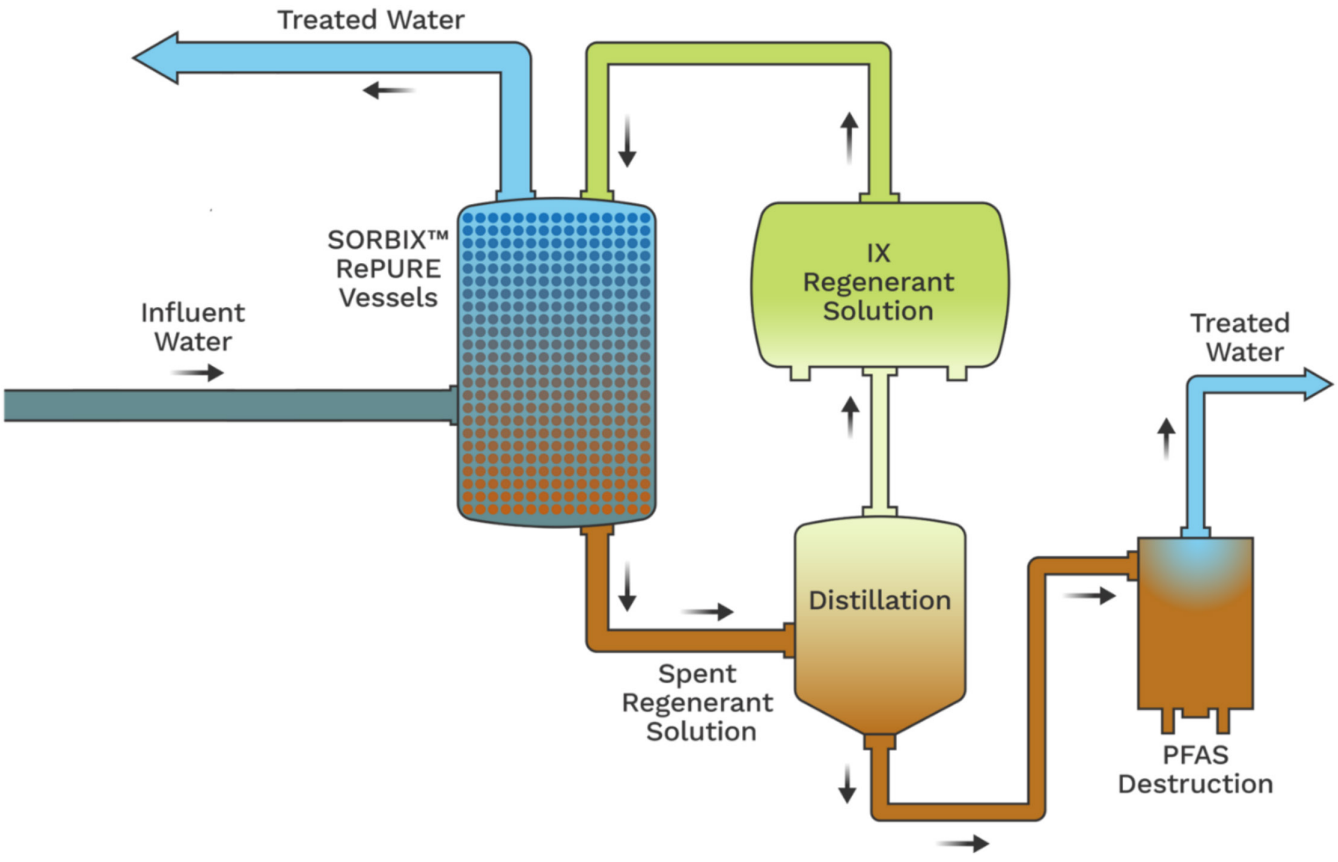

FIGURE 1 | IXR schematic showing typical IX regeneration process flow before liquid PFAS destruction step.

ready for direct liquid destruction or further concentration through Superloading. Superloading involves concentrating still bottoms into a solid waste that can be sent to landfill or destroyed using solid destruction technologies such as SCWO or incineration, as described in other sections of this paper (Chiang et al. 2023; US EPA 2024b). IXR coupled with Superloading can achieve a concentration factor of over one million to one (volume of water treated to volume of superloaded media) and can be operated for years before changeout is needed (Houtz, Pinkard, and Millewolte 2024).

IXR has a TReL value of 9, as reflected by nine full-scale PFAS IXR systems at defense and industrial sites globally with operating flows between 200 and 8000 GPM and startup dates as early as the mid-2010s. Two additional full-scale systems are being installed at industrial sites and are scheduled to start treating water in 2025. Full-scale data from 26 consecutive regeneration cycles show no PFAS buildup or deterioration of the IX resin (Kempisty et al. 2024).

Although IXR systems have often been used for industrial wastewaters containing high PFAS concentrations (i.e., $>1\,\mu g/L$) (Boyer et al. 2021; Kempisty et al. 2024), IXR has also shown promise in its treatment of PFAS for drinking water applications. US IXR drinking water systems are currently under development and should become available within the next couple of years.

3.1.3 | Onsite Regenerable GAC With Liquid-Phase Destruction (TRL = 4–5)

Water treatment facilities using GAC are often constrained by changeout logistics such as space, percent uptime requirements, and operating budgets, especially when frequent changeouts are required. Onsite GAC regeneration has the potential to reduce operating costs and logistics relative to changeout, disposal, and replacement of single-use GAC. An emerging, onsite technology from Revive Environmental known as GAC RENEW employs nonthermal, low-energy regeneration that can extend the useful life of new or existing GAC media. PFAS are extracted from the spent GAC media and concentrated into a solvent solution. The solvent can then be recovered through distillation or filtration, further concentrating PFAS into a smaller aqueous volume well suited for destruction with SCWO. The recovered solvent fraction can be reused for further GAC regeneration cycles. Figure 2 illustrates process flows for two example implementation scenarios using onsite regeneration of GAC with either onsite or

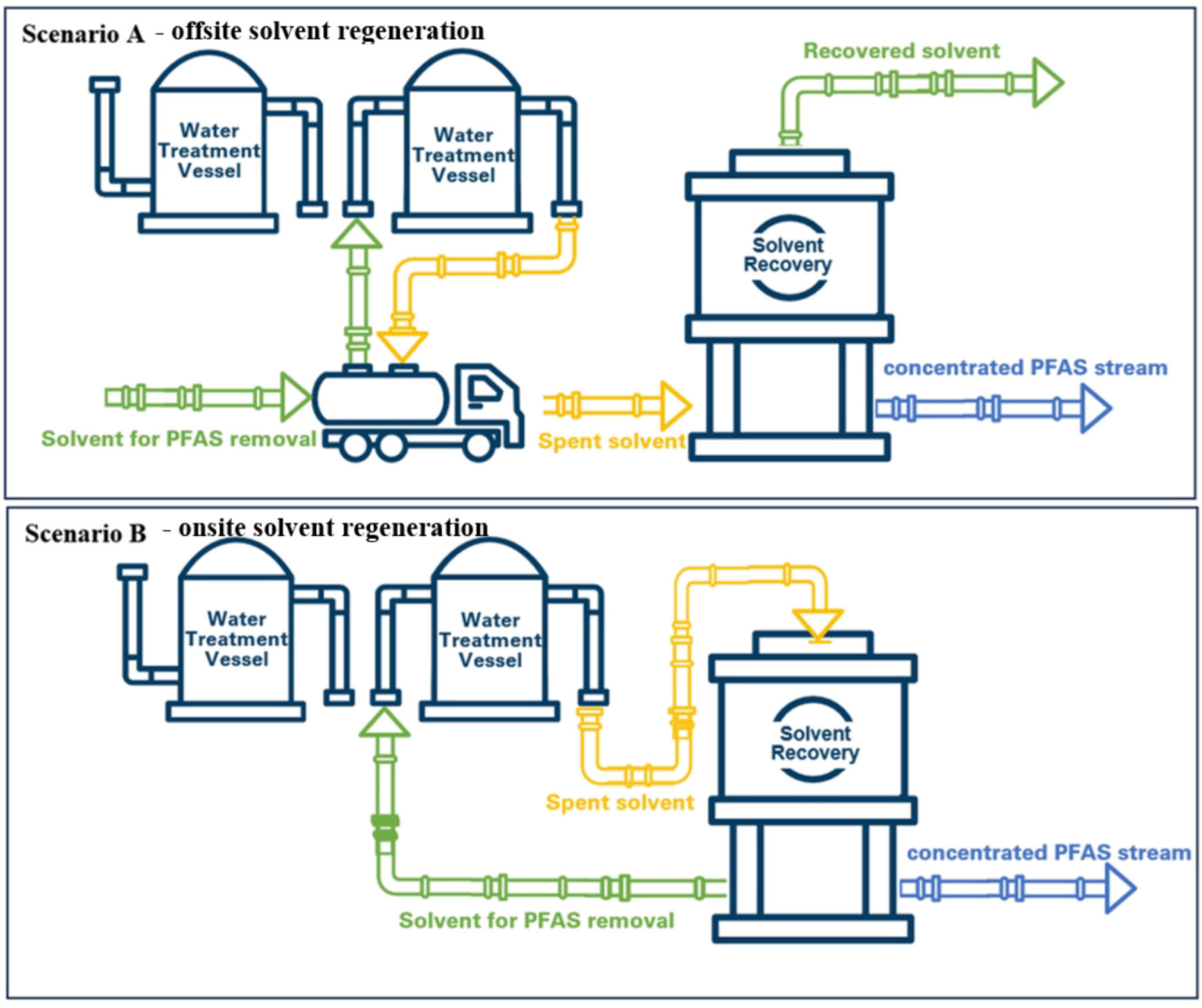

FIGURE 2 | Proposed GAC regeneration scenarios.

offsite solvent recovery. Offsite solvent recovery (Scenario A) is more cost-effective at small- to medium-scale or fragmented systems where life-cycle costs of an onsite solvent recovery system would exceed those of transporting solvent to and from an external site. Onsite solvent recovery (Scenario B) is most cost-effective at large-scale or centralized treatment systems where the economy of scale justifies higher capital expenditures to save on operating costs.

GAC regeneration via solvent extraction is driven by two key mechanisms. First, the use of a polar organic solvent disrupts the hydrophobic interactions of PFAS and GAC, which are believed to behave as the dominant PFAS sorption mechanism (Woodard et al. 2017). Second, electrostatic interactions between anionic PFAS and carbon surfaces are interrupted by increasing solvent pH to create a more negatively charged sorbent surface (Du et al. 2014). The efficiency of PFAS desorption into the solvent is impacted by several additional factors including sorbent surface properties, environmental conditions, and amount of PFAS sorbed (Watanabe et al. 2016).

The timing of solvent regeneration will be driven by the same decision criteria that drive changeout of single-use GAC. Once the adsorption vessel with solvent-regenerated GAC is placed back in service with the solvent-regenerated GAC, the remaining process is not impacted, and sites can track PFAS levels in effluent to monitor breakthrough. Preliminary bench studies evaluating repeated solvent regeneration of the same GAC have been conducted through four regeneration cycles. After four cycles, solvent-regenerated GAC adsorbed PFOS and PFOA from a spiked laboratory solution at similar levels (> 99% similar) to virgin GAC (Siriwardena et al. 2021). Revive Environmental is running concurrent breakthrough studies and onsite, side-by-side testing comparing filtration capacity and breakthrough timing of regenerated GAC versus virgin GAC (Stegner 2024).

Solvent recovery is the second component important to maintaining the efficiency of GAC regeneration. Laboratory scale recovery studies indicate no volatile loss of solvent during solvent recovery. Initial work suggests that a taller or more effective distillation column or rotary evaporation could show promise in eliminating PFAS from the recovered solvent (i.e., nondetect levels of PFAS chemicals in the distillate solution) (Ellis et al. 2025; Siriwardena et al. 2021), but this remains to be evaluated at the full scale. These results are encouraging in the effort to reduce the volume of residuals requiring ultimate disposal, with a concentration factor of 2000–4000 volumes of regenerant per volume of distilled residuals. Solvent recovery could be implemented at a centralized facility (Scenario A) or onsite (Scenario B).

Onsite GAC regeneration was assessed to have a TRL value of 4–5. This value is based on information from October 2024, when Revive Environmental successfully completed drum scale regeneration using GAC RENEW technology with several mobile regeneration events (Scenario A) executed as of October 2024. In November 2024, Revive Environmental expanded their pilot capacity to accommodate jobs in the range of 450–900 kg of GAC through sequential batch regeneration. A dedicated system for nonpotable applications will be commissioned in July 2025 to increase capacity to 27,000 kg per month (Stegner 2024). This capacity will service anticipated increased volumes of GAC for ground water remediation and industrial wastewater systems in the Midwest. Large scale capacity fully dedicated to potable-use GAC will be available in the first to second quarter of 2026 in the Midwest and New England regions of the United States, and further expansion to the west coast is planned by 2027 (Stegner 2024).

3.1.4 | Bench-Scale Technologies for GAC/AER Regeneration (TRL = 2–3)

Multiple bench-scale studies have demonstrated GAC or AER regeneration through means other than solvent regeneration. Remaining uncertainties regarding these methods include the conceptual design for on-site regeneration, full-scale rinsing and reservicing procedures, proportion of media mass loss through the process, production of PFAS intermediates, effect of other sorbed ions on regeneration and degradation efficacy, and changes in adsorptive capacity after multiple reactivation cycles and in continuous-flow conditions.

HALT can be used to treat liquids or slurries and combines elevated temperature, pressure, and pH (typically 350°C, 16.5 MPa, and 1-M NaOH) to degrade PFAS and other contaminants (Soker et al. 2023). HALT has demonstrated the ability to destroy ultra-short chain trifluoroacetic acid (TFA) and trifluoromethesulfonic acid (TFMS) (Austin et al. 2024; Houtz, Pinkard, and Millewolte 2024; Pinkard et al. 2024). One recent study applied HALT to slurried, spent GAC and found near complete (> 97%) reduction in measured concentrations of 11 targeted PFAAs. HALT-regenerated GAC had similar specific surface area to virgin GAC and also retained the ability to adsorb PFAS under batch equilibrium conditions (Soker et al. 2023). HALT is currently being commercialized by Aquagga for liquid feedstocks, with pilot-scale and full-scale units up to 480 gal/day, but HALT for GAC reactivation has not been demonstrated beyond the bench-scale and remains at a low TRL, with unknown applicability for potable water applications.

ARPs operate at ambient temperature and pressure to degrade contaminants through generation of hydrated electrons. ARPs can generate hydrated electrons through a variety of chemical and photolytic energy sources, including UV in the presence of sulfite and/or iodide, polarized hydrogen, and palladium nanoparticle catalysts (Houtz, Kempisty, and Lester 2024). Recent studies found effective regeneration of a weak base AER, with concurrent degradation of PFOA in suspended, high-pH, batch processes using UV–sulfite. Increased doses of sulfite increased PFOA recovery and degradation, up to 87% PFOA degradation. However, NOM sorbed to the AER was not destroyed by the ARP, resulting in decreased PFOA and organic adsorption capacity over six regeneration cycles (Cui and Deng 2023a, 2023b). ARPs for AER regeneration could be an alternate AER regeneration option, but they have not been demonstrated beyond the bench scale, and their applicability in drinking water applications remains unknown.

Other bench-demonstrated technologies to reactive spent media (TRL 2–3) include microwave regeneration of GAC

(Gagliano et al. 2021), supercritical CO_2 reactivation of GAC (Didenko et al. 2024), plasma reactivation of AER or GAC (Bailey 2021), thermal reactivation of AER (Dastgheib et al. 2021), and piezoelectric ball milling reactivation of AER (Zhu et al. 2025).

3.2 | Technologies to Destroy PFAS in Treatment Residuals

3.2.1 | High-Temperature Incineration for Single-Use Disposal of GAC/AER (TRL = 9)

The EPA's "Interim Guidance on the Destruction and Disposal of PFAS" lists landfilling, deep-well injection, and thermal treatment (incineration) as commercially viable full-scale technologies for disposal of PFAS wastes, including spent adsorption media (US EPA 2024b). High temperatures, sometimes exceeding 1000°C, are required to mineralize all PFAS, but required temperatures vary by compound and by incinerator operation and residence time (Winchell et al. 2021, 2024). Compounds with shorter chain lengths, sulfonic acid groups, and/or higher degrees of fluorination generally require higher temperatures for defluorination (US EPA 2024b). Addition of calcium or aluminum minerals could potentially lower the temperature needed to thermally defluorinate PFAS, but these have not been studied at full-scale (Wang et al. 2015). Most high-temperature incinerators operate using rotary kiln combustion with solid retention times around 1 h. PFAS destruction likely occurs in secondary afterburners operated at 1100°C–1370°C after desorption and volatilization to gas phase, with gas retention times around 2 s (US EPA 2024b).

Limited data are available on full PFAS defluorination in commercial, high-temperature incineration facilities accepting PFAS waste, which include hazardous waste incinerators, cement kilns, and lightweight aggregate kilns (Patterson and Dastgheib 2020; US EPA 2024c). Previous studies have found over 99.99% removal of targeted PFAS under specific conditions (Clean Harbors Inc 2023; Focus Environmental Inc 2020). However, incineration conditions used in these studies are not universal in full-scale high-temperature incineration facilities (US EPA 2024c). In addition, reported measurements of a limited number of targeted PFAS do not reflect the potential for chemical transformations to other, nontarget PFAS (Smith et al. 2024). One study specifically reported pilot-scale incineration conditions where > 99.9% removal of targeted PFAS was achieved but emissions of nontarget PFAS was detected through nontarget analysis (Shields et al. 2023).

High-temperature incineration of PFAS-laden spent media has notable drawbacks, including high energy requirements and fees (about $1300/short ton or $1400/metric ton), making it less economically feasible for facilities with high media use rates. Additionally, regulatory status of high-temperature incineration remains uncertain following recent moratoriums on incineration of PFAS wastes in Illinois, New York, and at Department of Defense sites (Illinois State Legislature 2022; New orkY State Legislature 2020; US Department of Defense 2023). Balancing these factors is crucial for determining the viability of high-temperature incineration of PFAS-laden spent media.

3.2.2 | Centralized Thermal GAC Reactivation (TRL = 9)

Offsite thermal GAC reactivation is commercially available, with about 17 facilities operating in the United States (US EPA 2024b). The process involve drying (100°C), desorption (100°C–250°C), pyrolysis (200°C–750°C), and oxidation (800°C–1000°C) steps, with total residence times around 2 h (Redding 2024). Similar to high-temperature incinerators, most PFAS destruction occurs in afterburners with temperatures above 885°C (US EPA 2024b). This process has similar PFAS removal efficiency and uncertainties as high-temperature incineration, with over 99.99% destruction of targeted PFAS through the combination of thermal treatment and air pollution control. Most GAC reactivation facilities are operated by GAC vendors, which then deliver the reactivated product back to the original user or place in it a general pool for purchase. Relative to high-temperature incineration, offsite thermal GAC reactivation can reduce media disposal and replacement costs, reduce greenhouse gas impacts by 80%, and secure future supply (if reusing reactivated GAC) (Redding 2024).

The reactivation process causes GAC mesopores to evolve and in some cases, improves PFAS sorption capacity (Redding 2024). Thermally reactivated GAC has demonstrated comparable PFAS removal performance to virgin GAC when returned to the same site for reuse (McNamara et al. 2018). GAC reactivation facilities typically limit site-specific reactivation contracts to larger facilities (exceeding 36,000 kg or 80,000 pounds carbon per changeout event), so effective use of thermally reactivated GAC is limited to larger facilities (at least 1–5 MGD, depending on concentrations and water quality) (Barr Engineering Co. Hazen and Sawyer 2023). Smaller sites are unlikely to merit a site-specific reactivation contract with facility operators, but could use GAC reactivation as a disposal option, replacing spent media with virgin media. GAC reactivation requires transportation to the facility (and *from* the facility if reusing reactivated GAC at the same site), spent media testing prior to acceptance at the reactivation facility, and replacement of about 15%–30% of media lost in each reactivation cycle (Redding 2024; US EPA 2024b). Facilities reactivating and reusing their GAC may also need to purchase a "swing load," or extra set of media to keep facilities operating while media is reactivated and later returned.

3.2.3 | Solid-Phase SCWO for Media Disposal (TRL = 7)

SCWO can be used to destroy and mineralize various organic contaminants, and has been demonstrated at bench- and pilot-scale for PFAS-laden GAC and AER (Chiang et al. 2023). SCWO involves the oxidation of organic compounds in water at supercritical conditions, which are achieved at temperatures above 374°C and pressures above 221 bar. Under these conditions, water exhibits unique properties, such as high diffusivity and low dielectric constant, which enhance the solubility of organic compounds (including PFAS) and oxygen, facilitating rapid oxidation (Krause et al. 2022). Fluorine separated from PFAS during SCWO can be precipitated as calcium fluoride through addition of calcium salts.

SCWO can achieve near-complete destruction of PFAS and other organic contaminants sorbed to spent media, with over 99% removal of both short-chain and total PFAS in a recent bench study

(Chiang et al. 2023). The process occurs quickly, with reaction times around 10 s, making SCWO suitable for high-throughput applications. The primary byproducts of GAC and AER destruction via SCWO are carbon dioxide, water, and inorganic salts. Disposal of spent media via SCWO also carries the potential for significant energy recovery, as both GAC and AER are high-energy feedstocks. Current operating data suggest that SCWO may not require external fuel or energy inputs when fed with GAC or AER (Viswanathan 2024). Unlike high-temperature incineration or GAC reactivation that may generate secondary pollutants or products of incomplete combustion, SCWO minimizes secondary waste production and air emissions (Divine et al. 2023; Meegoda et al. 2022).

Spent GAC and AER require milling and slurrying before SCWO treatment. The first step is to crush and mill the media to a fine particle size to aid suspension in water. To keep the crushed media suspended, dispersants or surfactants like sodium dodecyl sulfate can be added to reduce the surface tension between the particles and water. The choice and quantity of chemical used can be predetermined using a bench scale study prior to full scale implementation. Additional liquid is also added to increase water content from the typical 50% water content of spent media to a pumpable slurry with at least 80% water. Once homogenized, the feedstock is continuously agitated with a mixer, then pressurized and heated to reach supercritical water conditions.

SCWO has been applied at full-scale for other organic contaminants and is undergoing full-scale pilot testing for treating PFAS in biosolids and spent media. Spent GAC and spent AER containing PFAS were each prepared into slurries with 90%–95% water for a recent full-scale, continuous demonstration. Demonstration tests were conducted with 90 kg (dry) of spent GAC and 500 kg (dry) of spent AER, corresponding to slurry volumes of 1500 and 5000 L, respectively. An emulsifier was added to produce a homogenous and stable slurry for consistent feeding into the SCWO reactor. Adding an emulsifier increased viscosity, reduced particle settling, and produced uniform and homogenous feedstock. A low concentration of the emulsifier minimized material costs while also reducing the risk of ancillary chemical introduction at excessive levels. The suspension was further optimized, and the slurry was engineered to a certain micron-sized particle distribution, balancing pumpability against suspension stability. Caustic agents were added to achieve the optimal pH to prevent reactor fouling or scaling during SCWO operations (Viswanathan 2024).

This optimized preparation methodology allowed for stable slurry characteristics under handling, storage, and continuous feed into the SCWO reactor. Operational data demonstrated that the SCWO reactor design and feed preparation methodology were robust and scalable for a wide variety of adsorbent and resin feedstocks (Viswanathan 2024).

3.2.4 | Liquid Destruction Options for Managing Spent Regenerant (TRL = 3–7)

A variety of destruction technologies have been demonstrated as effective at destroying PFAS in liquid residuals, including spent regenerant from IXR and GAC regeneration. These include nonthermal plasma, electrochemical oxidation (EC), HALT, and UV-ARPs (Houtz, Pinkard, and Millewolte 2024; Liang et al. 2022; Maldonado et al. 2021; Singh et al. 2020). High concentrations of salt, NOM, and nitrate in IXR still bottoms (up to 5% sodium chloride) can slow PFAS destruction kinetics in plasma, EO, and UV-ARP systems (Liang et al. 2022). HALT is a technology that is not significantly impacted by these matrix constituents in IXR still bottoms and was selected for use in developing full pathway energy use and cost estimates for IXR (Houtz, Pinkard, and Millewolte 2024). SCWO for liquid wastes was selected as the destruction technology for spent GAC regenerant due to the synergies with Revive Environmental technology offerings.

3.3 | Viable Spent Media Management Pathways Selected for Detailed Evaluation

Technologies to remove PFAS from treatment vessels were combined with residuals management technologies into seven spent media management pathways with combined TRLs higher than 5:

- AER, media changeout, and offsite high-temperature incineration
- AER, media changeout, and offsite solid-phase SCWO destruction
- AER, onsite IXR regeneration, and offsite liquid-phase HALT disposal of still bottoms
- GAC, media changeout, and offsite thermal reactivation and reuse
- GAC, media changeout, and offsite high-temperature incineration
- GAC, media changeout, and offsite solid-phase SCWO destruction
- GAC, onsite regeneration (onsite or offsite solvent recovery), and offsite liquid-phase SCWO disposal of spent solvent

These pathways are diagrammed in Figure 3, with selected disposal technologies highlighted with bold font.

3.4 | Comparison of Project Energy Use and Costs

Figures 4 and 5 summarize estimated energy use and operational costs for the seven spent media management pathways presented above. Costs for electricity and energy use shown are included in O&M costs, but energy use is called out separately. Capital costs are not included as previously described. The unit used for analysis is per kilogram of dry, spent media that is regenerated, reactivated, or destroyed. This unit was selected to reduce the number of assumptions required about a given system. However, the interval between regeneration, reactivation, or changeout will vary between media types and between applications. Thus, estimated costs and energy use are not directly comparable between media type and should be considered jointly with estimated media use rates. Specific assumptions used in the analysis and their sources are detailed in Tables 2 and S1.

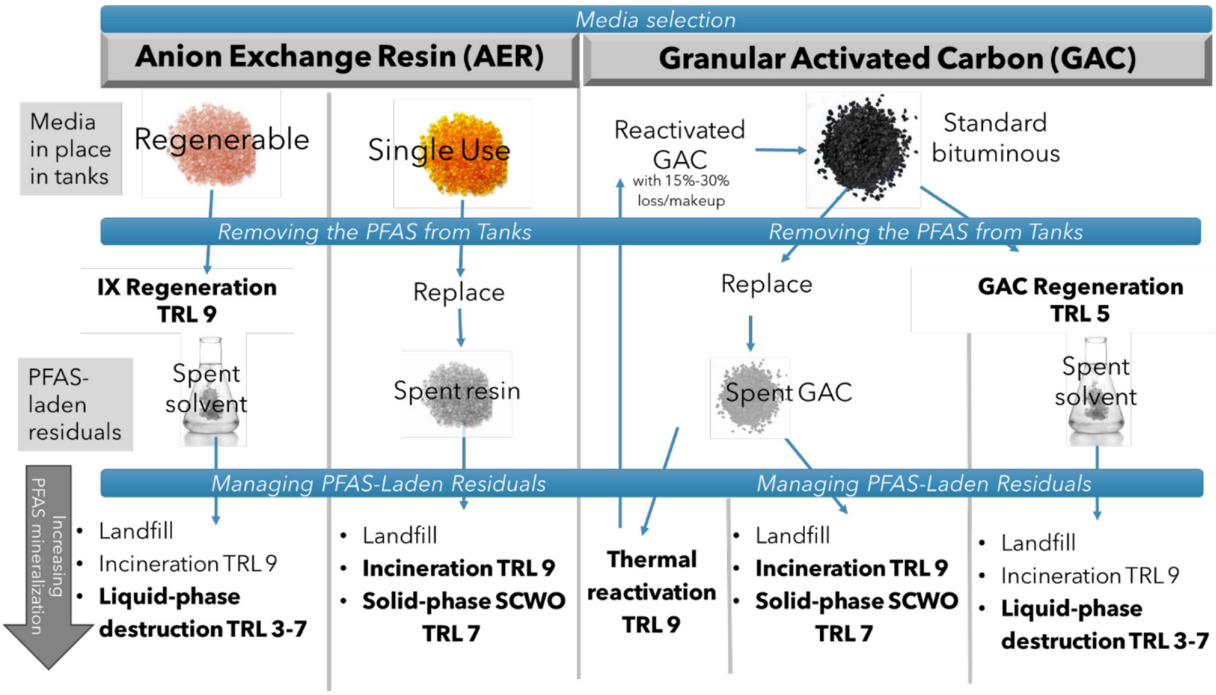

FIGURE 3 | Summary of management pathways for spent, PFAS-laden sorption media.

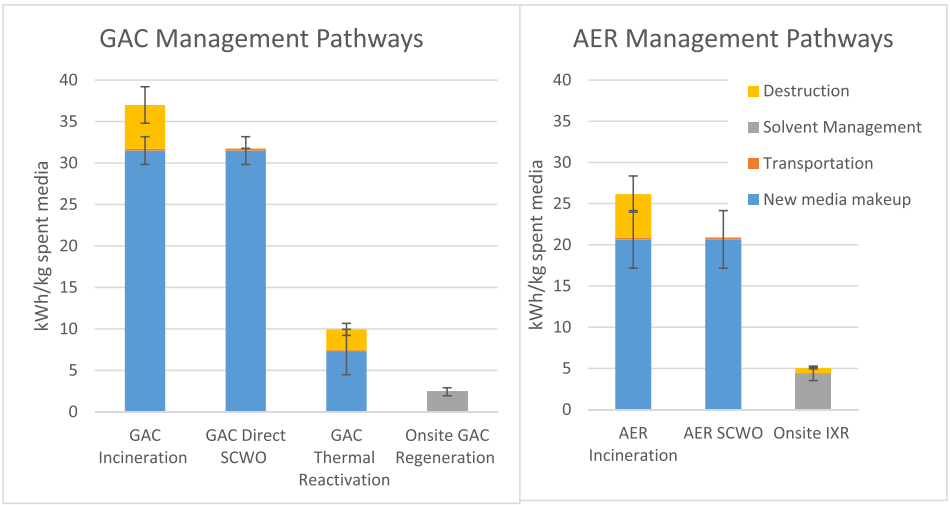

FIGURE 4 | Estimated energy usage for spent media management pathways. Uncertainty bars are shown for new media makeup, destruction, and solvent management components.

The provision of virgin media is the largest contributor to both energy use and operational costs. As a result, pathways that minimize virgin media makeup have lower costs. Costs estimated for onsite regeneration do not include capital equipment for regeneration equipment, so the difference in life-cycle costs will be less than the difference in O&M costs reflected here. Generally, single-use AER with offsite disposal consumes less energy per mass media than single-use GAC but is more costly due to higher media prices. Energy use and costs associated with transportation of virgin and spent media is nearly negligible, accounting for less than 2% of total energy use and costs for a given spent media management pathway.

4 | Discussion

4.1 | Project-Specific Factors Affecting Decision Making

Spent media management should be considered as part of design and equipment selection, including planning adequate space to facilitate spent media removal and replacement or regeneration. Decisions about spent media management need to address how to change out or regenerate spent media and how to dispose of residuals. Related design questions about media selection and prediction of media breakthrough and use rates will inform

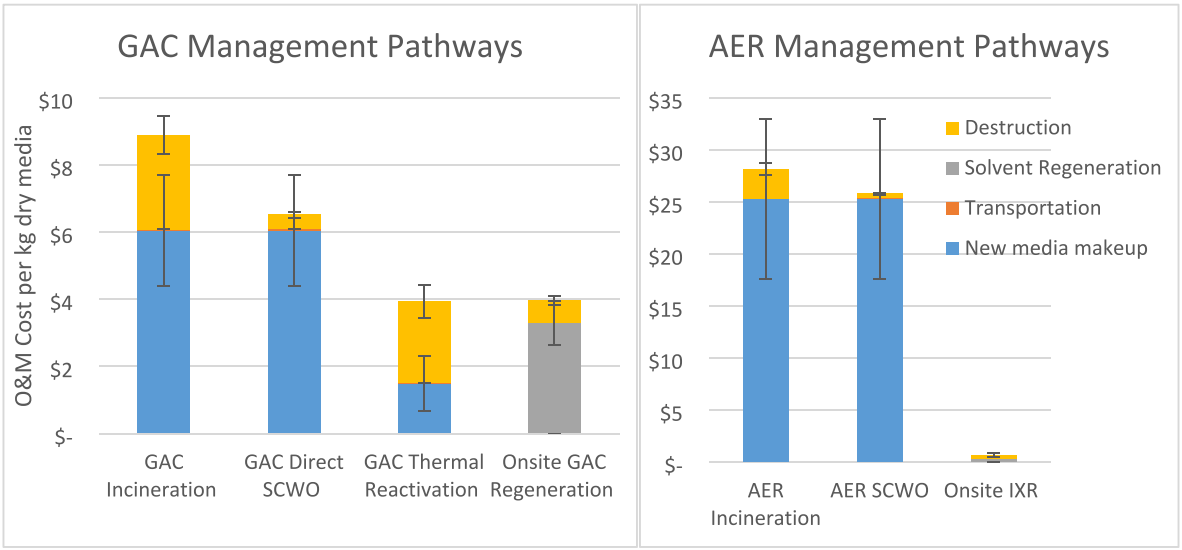

FIGURE 5 | Estimated operations and maintenance costs for spent media management pathways. Uncertainty bars are shown for new media makeup and destruction components.

what type spent media management pathways are available and influence which are most cost-effective. In some cases, decision making will be influenced by what the equipment provider or manufacturer can facilitate directly or that a third party is able to accommodate.

Outlining a spent media management pathway for a specific facility involves evaluating site-specific needs. Project-specific factors that influence pathway selection include type of media used (if already determined), media use rates, influent water quality, facility size and location, and final PFAS fate.

Spent media management choices are intertwined with media selection choices, which are not the focus of this paper. Those looking for guidance on media selection should refer to other recent publications on the topic (Boyer et al. 2021; Ellis et al. 2022; Gagliano et al. 2020; Grieco et al. 2021; Lei et al. 2023; Medina et al. 2022). Briefly, AER is more expensive than GAC per mass of media but has longer bed life, typically higher removal efficiency for short-chain PFAS, and shorter empty-bed contact times (EBCTs), enabling smaller vessels and less media used per unit water treated. However, AER is more susceptible than GAC to fouling and scaling from high concentrations of organic carbon, iron, and competing anions in feed water with limited pretreatment. While disposal options are available to any media type, AER regeneration is more widely demonstrated to date, and thermal reactivation currently is only available for GAC. In addition to cost, media supply and total domestic disposal capacity will be a major factor in the decision process for treatment systems. Reusing GAC and AER can help assure media supply for a site and reduce costs and energy use associated with virgin media production and destruction.

Facility size also informs spent media management decisions. Media changeout costs will be a smaller proportion of O&M costs for smaller facilities, so there will be less incentive to purchase onsite regeneration equipment to save changeout and media costs. Additionally, ongoing reuse of thermally reactivated GAC is most effective at sites large enough to merit a site-specific reactivation contract with facility operators (Barr Engineering Co. Hazen and Sawyer 2023; McNamara et al. 2018).

Facility location and proximity to existing and future regeneration, reactivation, and disposal sites can also impact decision making. As more industrial wastewater and municipal drinking water plants implement sorption and anion exchange treatment to manage PFAS, construction of additional and more dispersed regional spent media facilities could simplify waste management, with the potential for lowered operating facility costs, reduced long-distance transportation, and lower risk of secondary contamination. Regional facilities could provide offsite regeneration of either IXR or GAC, media destruction using SCWO, or increased GAC reactivation capacity. One study evaluated centralized SCWO treatment and found a positive business case for handling biosolids in Maine (Carpenter et al. 2023). A similar study evaluating regional spent media management options could elucidate which geographic regions benefit economically from a regional facility. Any future waste regulation that changes status of PFAS-laden spent media has the potential to increase transportation costs, which would affect considerations for management pathways and facility siting. One early example of regionalized PFAS destruction comes from Revive Environmental, which operates “hub-and-spoke” facilities accepting liquid waste streams for SCWO disposal, all registered as hazardous waste handling locations (Stegner 2024).

Final PFAS fate differs across different spent media management options, both on timescales and destruction efficacy. Differences in PFAS fate were detailed previously in this paper. Projects that require or prioritize full destruction have a range of options available. Other factors that might impact technology selection include secondary waste production and ease of integration into existing treatment systems.

Specific considerations by technology are illustrated in Figure 6 and detailed in Table S3.

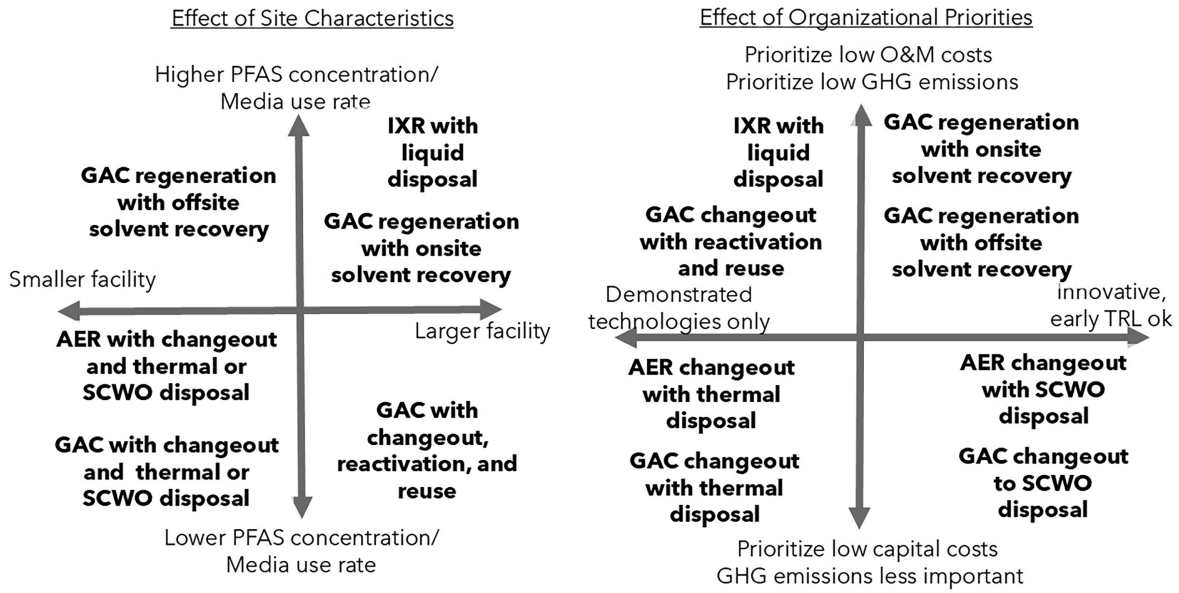

FIGURE 6 | Spent media management decision-making framework.

4.2 | Estimating Media Changeout/Regeneration Frequency

The functional unit of concern for most water treatment facilities is "per volume of water treated," which differs from the "per dry mass of media" functional unit used in this study. Facilities looking to estimate annual energy use and O&M costs should separately estimate their annual media use rates, then multiply those estimates by the provided energy use and O&M costs per mass of media presented here. Generally, media use rates for AER are a factor of 2–10 lower than for GAC (Chow et al. 2022; Woodard et al. 2017), and regenerable ion exchange media may be regenerated more frequently than similar single-use media changed out (Ellis et al. 2022). Media use rates for a given media are often dictated by treatment targets and influent water quality, especially concentrations of PFAS concentrations and nontarget constituents (e.g., NOM). Targeting removal of short-chain PFAS increases media use rates, because they are more water soluble and thus less amenable for removal onto solid media. For example, removing four-carbon PFAS increases GAC use rates by factors of 2–10 relative to removing eight-carbon PFAS (Burkhardt et al. 2019; Franke et al. 2021; Westreich et al. 2018). As an example, Ellis and colleagues compared costs for GAC and AER treatment with varying media use rates (Ellis et al. 2023). Media use rates can be estimated with increasing levels of accuracy through modeling (Burkhardt et al. 2022; Burkhardt and Speth 2020), bench-scale testing (Grieco et al. 2021; Schaefer et al. 2019), and pilot-scale testing.

4.3 | Considerations for Potable Water Applications

Selecting spent media management pathways for potable water treatment operations requires special considerations. Regulatory requirements for what media can be used in drinking water applications continue to evolve in the United States and abroad. The US EPA lists both ion exchange and GAC (in addition to membrane technologies) as "best available technologies" for removing PFAS from drinking water (US EPA 2024a). In some states, GAC use in potable applications to date has been limited to virgin GAC (Weum 2025). However, the use of reactivated GAC for potable use is increasing, with at least 50 drinking water facilities across 10 states planning implementation as of 2025 (BusinessWire 2025). A drinking water facility's spent GAC can be thermally reactivated as a custom batch in a NSF 61 certified, food-grade reactivation facility, then returned to the same drinking water facility and augmented with virgin GAC to account for reactivation losses (Calgon Carbon 2025). The American Water Works Association Standard B605 provides industry guidance for use of reactivated carbon (AWWA 2018). No states are currently allowing use of solvent regenerated GAC or AER. Spent media management where AER is used for drinking water treatment is presently limited to landfilling and incineration, driving increased selection of GAC over AER for drinking water treatment. Other factors driving use of GAC over AER include a broader range of contaminants removed and more drinking water installations to date.

Supply continuity and water quality consistency are relevant to all facilities, but critical requirements for drinking water. Continuity of treated water supply requires facilities to meet water demands while spent media is changed out and managed, with limited or no operational disruption to treatment operations or treated water availability. Drinking water systems also need to meet primary drinking water standards and maintain consistent delivered water quality. Utilities need to consider if spent media management partners are responsive and likely to continue to provide the same services for the life of any contract(s) entered into, if a selected spent media management pathway will be readily available with adequate planning, and if media changeout can be completed expeditiously and in coordination with replacement media installation to minimize treatment system downtime. In applications where custom-reactivated GAC

is acceptable replacement media, drinking water providers may require testing to verify that a consistent and effective replacement material is returned to use.

5 | Conclusions

The management of PFAS-laden, spent GAC and AER have emerged as a critical issue in drinking water and industrial wastewater sectors. This work addresses a key gap by summarizing and comparing spent media management pathways and highlighting project factors that impact decision making. Generally, high costs and energy use for single-use media procurement drive operating costs and energy use for PFAS treatment facilities. These energy demands typically stem from the energy-intensive resource extraction phase (e.g., anthracite mining), but specialized adsorbents like AERs often require large quantities of chemical inputs during synthesis (e.g., trimethylamine for exchange site amination) that lead to higher costs and emissions (Ellis et al. 2023). On the destruction side, GAC reactivation is competitive from both O&M cost and energy usage perspectives. Solid-phase SCWO could offer a lower energy option compared to incineration for sites with lower media use rates for either GAC or AER, but full-scale SCWO facilities accepting spent media are not yet available. Media regeneration offers lower operating costs per mass of spent media out than single-use operation, but potential project savings will depend on capital costs for regeneration equipment and how regeneration frequencies compare to changeout and disposal frequencies. When considering life-cycle energy usage, the energy used to produce virgin media to replace single-use media systems remains the most significant factor.

Site-specific factors that influence which management options are most practical include facility size and location, influent water quality, and type of media used (if already determined). Media regeneration and reactivation options are generally more economical at facilities treating larger flows and/or higher PFAS concentrations. While laboratory and pilot-scale studies provide promising data, there is a pressing need for full-scale validation to substantiate the effectiveness and economic viability of various media management and destruction technologies. Validating data through full-scale operations is essential to ensure real-world efficacy, comprehensive performance metrics, economic viability, regulatory compliance, scalability and reproducibility, environmental and safety considerations, and ongoing optimization and innovation.

Conflicts of Interest

Tiffany Stegner, Maggie Thompson, Sudhakhar Viswanathan, and Brian Pinkard are employees of companies that develop, demonstrate, and sell PFAS treatment technologies and/or services in the area of spent media management. Katie Wolohan and Don Richard are consultants at a company that has done work for and with similar technology companies in the past.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.