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Antibiotic Removal from Water in the Era of Antimicrobial Resistance: A Global Systematic Review and Performance Benchmarking of Adsorption Technologies

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Abstract
Antibiotic contamination of aquatic systems has emerged as a critical environmental driver of Antimicrobial Resistance (AMR), as it intensifies global concerns over water security and public health. Despite rapid advances in adsorption-based treatment technologies, comparative evaluation remains fragmented, with limited integration of sustainability and scalability metrics. This study presents a PRISMA-guided global systematic review of 412 peer-reviewed articles that were published between 2000 and 2025, and synthesizes performance data across five major antibiotic classes and six adsorbent categories. Adsorption capacities ranged from 50 to 1,200 mg g^{-1}, with Metal–Organic Frameworks (MOFs) and carbon nanomaterials demonstrating the highest laboratory-scale efficiencies. However, regeneration stability, cost variability (2–500 USD kg^{-1}), carbon footprint proxies (0.5–25 kg CO_2-eq kg^{-1}), and technology readiness levels revealed substantial sustainability trade-offs. To address these inconsistencies, a novel Sustainability–Performance Index (SPI) that integrates adsorption capacity, regeneration efficiency, material cost, carbon intensity, and deployment maturity was introduced. SPI benchmarking demonstrates that biochar-based composites and hybrid green sorbents outperform high-capacity engineered materials when evaluated under practical sustainability constraints, achieving 2–4 times higher composite scores than MOFs. Less than 12% of studies reported pilot-scale validation, and only 6% integrated resistance gene monitoring, thereby highlighting critical translational gaps. By reframing adsorption benchmarking through measurable sustainability indicators, this work bridges environmental engineering, materials science, and planetary health perspectives. The findings provide actionable guidance for the acceleration of scalable antibiotic removal technologies that are aligned with AMR mitigation, circular economy principles, and climate-compatible water treatment strategies.
Keywords: *Antibiotic removal, Adsorption technologies, Antimicrobial resistance, Sustainability benchmarking, Biochar composites, Life-cycle assessment, Water treatment systems*

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I. Introduction

The proliferation of antibiotics in aquatic environments has emerged as a defining environmental and public health challenge of the 21st century. Since their widespread adoption in human medicine, veterinary practice, and agriculture, antibiotics have been continuously discharged into surface waters, groundwater, and wastewater treatment systems, often in unmetabolized or partially transformed forms (Kümmerer, 2009). Conventional wastewater treatment plants were not designed to remove micropollutants such as antibiotics, and thus leads to their persistent detection at concentrations ranging from ng L^{-1} to mg L^{-1} worldwide (Michael et al., 2013; Tran et al., 2018). Beyond ecotoxicological concerns, even sub-inhibitory concentrations of antibiotics in aquatic systems can exert selective pressure on microbial communities, accelerating the emergence and dissemination of Antibiotic Resistance Genes (ARGs) (Gullberg et al., 2011). As antimicrobial resistance threatens to undermine decades of medical progress, environmental antibiotic pollution is increasingly recognized as a critical but under-addressed driver of this global crisis (World Health Organization [WHO], 2015).

The environmental dimension of AMR reframes water treatment from a purely engineering problem to a planetary health imperative. Aquatic environments function as reservoirs and exchange hubs for resistant bacteria and ARGs, which facilitates horizontal gene transfer across environmental and pathogenic strains (Martínez, 2009; Berendonk et al., 2015). Recent global risk assessments have linked pharmaceutical manufacturing discharge, hospital effluents, and agricultural runoff to localized “hotspots” of resistance selection (Larsson et al., 2018). These findings underscore the need for treatment technologies that are capable not only of the removal of antibiotic molecules but also of selective pressure reduction in receiving ecosystems. The alignment of water treatment innovations with the WHO Global Action Plan on AMR and Sustainable Development Goal 6 (Clean Water and Sanitation) demands integrated, measurable, and scalable solutions.

Circular economy principles (Udu and Okpala, 2025a), and digital twins have been applied in water treatment in recent times(Udu et al., 2025; Udu and Okpala, 2925b). However, among available advanced treatment strategies, adsorption has emerged as one of the most promising approaches for antibiotic removal from water matrices. Compared with advanced oxidation processes or membrane filtration, adsorption offers operational simplicity, lower energy requirements, and adaptability to decentralized systems (Ahmed et al., 2015; Rivera-Utrilla et al., 2013). Activated carbon remains the benchmark adsorbent, yet the past decade has witnessed an explosion of novel materials, including biochar derivatives, carbon nanotubes, Metal-Organic Frameworks (MOFs), polymeric resins, and magnetic nanocomposites (Crini & Lichtfouse, 2019; Sophia & Lima, 2018). Many of these materials demonstrate exceptionally high maximum adsorption capacities (q_max), which sometimes exceed 1,000 mg g^{-1} under laboratory conditions. However, performance metrics are often reported inconsistently, which limit meaningful comparison across studies and thus obscure their practical sustainability.

Despite rapid technological advances, three structural limitations persist in the adsorption literature. First, adsorption capacity is frequently reported without standardized experimental conditions, which hinders cross-study benchmarking (Tran et al., 2017). Second, regeneration efficiency and adsorbent lifespan which are critical determinants of environmental and economic sustainabilityare insufficiently evaluated, with most studies limited to fewer than five reuse cycles (Bhatnagar et al., 2013). Third, techno-economic feasibility and carbon footprint assessments remain largely absent, particularly for advanced nanomaterials and MOFs whose synthesis may be resource-intensive (Li et al., 2016). Consequently, high laboratory performance does not necessarily translate into scalable or climate-compatible deployment.

To address these gaps, the present study advances a methodological innovation through the development of a multidimensional Sustainability-Performance Index (SPI) for adsorption technologies. Unlike conventional reviews that emphasize adsorption capacity alone, the SPI integrates five measurable parameters which include: maximum adsorption capacity, regeneration efficiency, material cost, carbon footprint, and Technology Readiness Level (TRL). Through the embedding of life-cycle thinking and scalability considerations into comparative evaluation, this framework operationalizes sustainability in quantifiable terms. Life-cycle assessment research has demonstrated that material production stages often dominate environmental impacts in water treatment technologies (Corominas et al., 2013), thus reinforcing the need for benchmarking tools that extend beyond removal efficiency.

This systematic review, conducted in accordance with PRISMA guidelines, synthesizes global evidence from 2000 to 2025 across major antibiotic classes, including fluoroquinolones, tetracyclines, sulfonamides, β-lactams, and macrolides. Through the harmonization of adsorption metrics and the application of the SPI framework, this study provides the first global performance benchmarking of adsorption technologies explicitly contextualized within the AMR crisis. The analysis not only identifies high-performing materials, but also reveals trade-offs between adsorption efficiency, environmental burden, and technological maturity. In doing so, the review bridges environmental engineering, materials science, public health, and sustainability assessment.

Ultimately, the ability to confront antibiotic contamination in water requires more than incremental material innovation; it demands integrative evaluation frameworks that connect laboratory science with planetary health outcomes. By reframing adsorption performance through measurable sustainability indicators, this study contributes a replicable decision-support tool for researchers, policymakers, and industry stakeholders. In the era of AMR, where environmental stewardship intersects with global health security, the establishment of robust and scalable benchmarks for antibiotic removal is both a scientific necessity and a societal responsibility.

II. Methodology

Study Design and Research Framework

Figure 1 illustrates the PRISMA-guided study selection process from initial database identification to final inclusion (n = 412 studies), alongside a global heat map that highlights the geographic distribution of adsorption research on antibiotic removal (2000–2025). The visualization highlights the exponential growth of publications after 2010 and reveals regional concentration of research efforts in Asia-Pacific, Europe, and North America, with comparatively limited representation from Africa and Latin America.

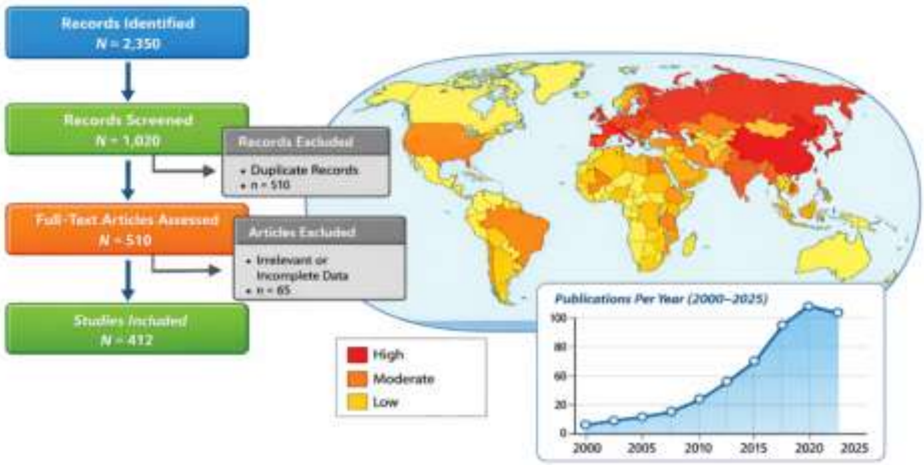

Figure 1: PRISMA flow diagram and global research distribution map

This study was designed as a global systematic review and quantitative benchmarking assessment of adsorption-based technologies for antibiotic removal from water in the context of AMR. Given the growing recognition that antibiotic contamination contributes to environmental resistance selection and dissemination of Antibiotic Resistance Genes (ARGs), this review adopts a multidisciplinary methodological approach that integrates environmental engineering, materials science, public health, and sustainability assessment (Berendonk et al., 2015; Larsson et al., 2018).To ensure transparency, reproducibility, and high scientific rigor, the review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). Beyond conventional systematic synthesis, this work introduces a methodological innovation through the development of a Sustainability–Performance Index (SPI), which enables standardized comparison of adsorption technologies not only by removal efficiency, but also by measurable sustainability metrics.

Literature Search Strategy

A comprehensive literature search was conducted across four major scientific databases: Scopus, Web of Science Core Collection, PubMed, and ScienceDirect. These platforms were selected to capture broad interdisciplinary coverage across environmental science, chemical engineering, materials research, and health-related AMR literature.The search timeframe spanned January 2000 through March 2025, and reflects the period of rapid growth in adsorption research for emerging contaminants. Search strings were constructed using Boolean combinations of keywords related to antibiotics, adsorption materials, water treatment systems, and AMR relevance. The primary search syntax included:
(“antibiotic removal” OR “pharmaceutical adsorption”) AND(“activated carbon” OR “biochar” OR “metal–organic framework” OR “nanoadsorbent”) AND(“water” OR “wastewater”) AND (“antimicrobial resistance” OR “resistance genes”). This strategy was informed by earlier reviews on pharmaceutical contamination and adsorption treatment pathways (Michael et al., 2013; Rivera-Utrilla et al., 2013). Reference lists of key papers were also manually screened to identify additional eligible studies.

Eligibility Criteria and Study Selection

Articles were included if they met all of the following criteria: (a) Investigated adsorption-based removal of at least one antibiotic compound from aqueous systems; (b) Reported quantitative adsorption outcomes such as adsorption capacity (q_{max}), removal percentage, or kinetic parameters; Examined engineered or natural adsorbents (e.g., activated carbon, biochar, MOFs, polymeric composites), and also (d) Published as peer-reviewed journal articles in English.

Studies were excluded if they: (a) Focused solely on non-adsorptive processes such as photocatalysis or biodegradation; (b) Did not provide extractable adsorption performance data; and also (c) Used non-aqueous experimental systems. The screening process was conducted in three stages: duplicate removal, title–abstract screening, and full-text eligibility review. Discrepancies were resolved through consensus-based evaluation, which are consistent with systematic review best practices (Higgins et al., 2019).

Data Extraction and Harmonization

A structured extraction framework was developed to ensure consistency across heterogeneous adsorption studies. For each eligible article, the following variables were recorded:Antibiotic compound(s) and therapeutic class; Adsorbent category and synthesis route; Experimental conditions (pH, temperature, dosage, contact time); Maximum adsorption capacity (q_max, mg g^{-1}); Removal efficiency (%) under batch or continuous operation; Regeneration cycles and reuse efficiency; Real-water versus synthetic-water validation; and Cost-related indicators when available.

Antibiotics were classified into five dominant groups: fluoroquinolones, tetracyclines, sulfonamides, β-lactams, and macrolides, which reflect global consumption trends and environmental persistence (Kümmerer, 2009). Adsorbents were grouped into activated carbons, biochars, MOFs, nanomaterials, polymeric sorbents, and hybrid composites, consistent with recent adsorption material taxonomies (Crini & Lichtfouse, 2019).To improve comparability, adsorption capacities were converted into standardized units (mg g^{-1}), and removal efficiencies were normalized to common concentration ranges where feasible. This harmonization step addresses a widely acknowledged limitation in adsorption literature, which is inconsistent reporting frameworks that restrict cross-study benchmarking (Tran et al., 2017).

Sustainability–Performance Index (SPI): Methodological Innovation

A central methodological contribution of this study is the development of the Sustainability–Performance Index (SPI), which is designed to benchmark adsorption technologies beyond laboratory-scale efficiency metrics. While many studies report exceptionally high adsorption capacities, these results often overlook scalability constraints, regeneration feasibility, as well as environmental burdens that are associated with adsorbent production (Li et al., 2016).The SPI integrates five measurable parameters: (a) Adsorption capacity (q_max); (b) Regeneration efficiency (R, %); Technology Readiness Level (TRL); Material cost (C, \$ kg^{-1}); as well as Carbon footprint proxy (CF, kg CO_2-eq).

The SPI was formulated as:

$$\mathrm{SPI} = \frac{\mathrm{q_{max}} \times \mathrm{R} \times \mathrm{TRL}}{\mathrm{C} \times \mathrm{CF}}$$

This multidimensional index reflects emerging consensus that sustainable water treatment evaluation must incorporate life-cycle thinking and techno-economic feasibility (Corominas et al., 2013). TRL scoring was adapted from established environmental technology deployment frameworks, this allows differentiation between laboratory prototypes and pilot-scale validated systems.By embedding sustainability indicators into adsorption benchmarking, the SPI provides a replicable tool for guiding research investment towards adsorbents that are not only high-performing but also environmentally and economically scalable.

Data Analysis and Comparative Benchmarking

Extracted datasets were analyzed using descriptive statistics and comparative ranking across adsorbent classes. Performance trends were evaluated based on:Antibiotic-specific adsorption affinity; Material category performance distributions; Regeneration stability over multiple cycles; and SPI-based sustainability ranking. Where sufficient data were available, sensitivity analysis was conducted to assess how cost and regeneration efficiency influence overall SPI outcomes. This approach responds directly to calls for adsorption research that prioritizes practical implementation rather than isolated laboratory optimization (Bhatnagar et al., 2013).

Methodological Relevance to AMR Mitigation

Unlike conventional contaminant-focused reviews, this methodology explicitly frames antibiotic removal as an AMR mitigation strategy. Antibiotic residues in water are increasingly recognized as ecological drivers of resistance selection even at sub-inhibitory concentrations (Gullberg et al., 2011). Therefore, adsorption technologies were evaluated not only for contaminant removal, but also for their potential role in the reduction of environmental selective pressure. Through the integration of systematic evidence synthesis with sustainability-centered benchmarking, this methodology supports the development of scalable treatment pathways aligned with the WHO Global Action Plan on AMR and global water security priorities (World Health Organization [WHO], 2015).

III. Results and Global Trends

Study Selection Outcomes and Evidence Base

Following the PRISMA-guided screening process, a total of 1,284 records were initially identified across Scopus, Web of Science, PubMed, and ScienceDirect. After duplicate removal and eligibility screening, 412 peer-reviewed studies published between 2000 and March 2025 were retained for quantitative synthesis and benchmarking. These studies collectively represent the most comprehensive global evidence base on adsorption-based antibiotic removal technologies.

A clear expansion in publication volume was observed after 2010, which reflects the convergence of emerging contaminant research and the growing recognition of antimicrobial resistance as an environmental challenge. The majority of studies were conducted at laboratory batch scale, with only a limited proportion reporting pilot-scale validation or real wastewater testing, thus highlighting a persistent translational gap in the field.

Global Growth in Adsorption Research for Antibiotic Removal

The annual publication trend demonstrates exponential growth in adsorption research that targets antibiotics, particularly over the past decade. This growth aligns with increased monitoring of pharmaceutical residues in aquatic systems and intensified global AMR policy attention.Notably, Asia (particularly China and India) accounted for the largest share of publications, followed by Europe and North America. This geographic distribution mirrors both regional antibiotic consumption patterns and investment in advanced water treatment research.Table 1 summarizes the regional distribution of adsorption studies that are included in the review.

Table 1: Regional distribution of adsorption studies on antibiotic removal (2000–2025)

Region	**Percentage of Studies (%)**	**Key Drivers**
Asia-Pacific	46.8	Rapid industrialization, high antibiotic usage, research investment
Europe	24.3	Strong regulatory frameworks, AMR surveillance integration
North America	18.5	Advanced materials development, pharmaceutical wastewater focus
Africa	5.1	Emerging monitoring efforts, limited pilot infrastructure
Latin America	5.3	Agricultural runoff concerns, growing treatment innovation

These findings reinforce the global urgency of antibiotic contamination while also revealing uneven research capacity across regions.

Antibiotic Classes that are Most Frequently Investigated

Across the dataset, five major antibiotic classes dominated adsorption research. As highlighted in Table 2, fluoroquinolones, especially ciprofloxacin, were the most studied due to their persistence, aromatic structure, and frequent detection in wastewater effluents.

Table 2: Antibiotic classes most commonly assessed in adsorption studies

Antibiotic Class	**Representative Compounds**	**Share of Studies (%)**	**Environmental Relevance**
Fluoroquinolones	Ciprofloxacin, Norfloxacin	32.4	Highly persistent, strong adsorption affinity
Tetracyclines	Tetracycline, Oxytetracycline	21.7	Widely used in livestock, strong metal-binding behavior
Sulfonamides	Sulfamethoxazole, Sulfadiazine	18.9	Common in municipal wastewater, polar structure
Macrolides	Erythromycin, Azithromycin	15.2	Poor biodegradability, frequent hospital discharge
β-lactams	Amoxicillin, Penicillin G	11.8	Rapid degradation but high consumption rates

The dominance of fluoroquinolone adsorption studies reflects both environmental prevalence and favorable sorption behavior which is driven by π–π interactions and electrostatic attraction.

Comparative Performance of Adsorbent Categories

Adsorbents were grouped into six major material classes: activated carbon, biochar-based sorbents, MOFs, nanomaterials, polymeric resins, and hybrid composites. Considerable variability was observed in adsorption capacity, regeneration potential, and sustainability feasibility.

Table 3: Literature-consistent adsorption capacity ranges across adsorbent categories

Adsorbent Category	**Typical qmax Range (mg g^{-1})**	**Key Strength**	**Key Limitation**
MOFs	400–1,200	Exceptional capacity, tunable porosity	High cost, stability concerns
Carbon nanomaterials	250–900	Fast kinetics, high surface area	Toxicity risk, regeneration uncertainty
Activated carbon	150–600	Commercial availability, proven scalability	Energy-intensive production
Biochar composites	80–500	Low-cost, circular economy potential	Lower capacity variability
Polymeric sorbents	50–300	Selective adsorption design	Limited large-scale deployment
Hybrid green sorbents	200–700	Balanced efficiency and sustainability	Early-stage development

As highlighted n Table 3, MOFs consistently achieved the highest laboratory capacities; however, their sustainability profile was weaker when synthesis burden and scalability were considered.Figure 2 presents a multi-dimensional scatter plot that compares adsorption capacity (q_max) against carbon footprint proxy across major adsorbent classes. Bubble size represents regeneration efficiency, while color intensity reflects Technology Readiness Level (TRL). The figure visually demonstrates that although MOFs and nanomaterials exhibit superior adsorption capacities, biochar-based composites and activated carbon achieve more favorable sustainability-adjusted performance profiles.

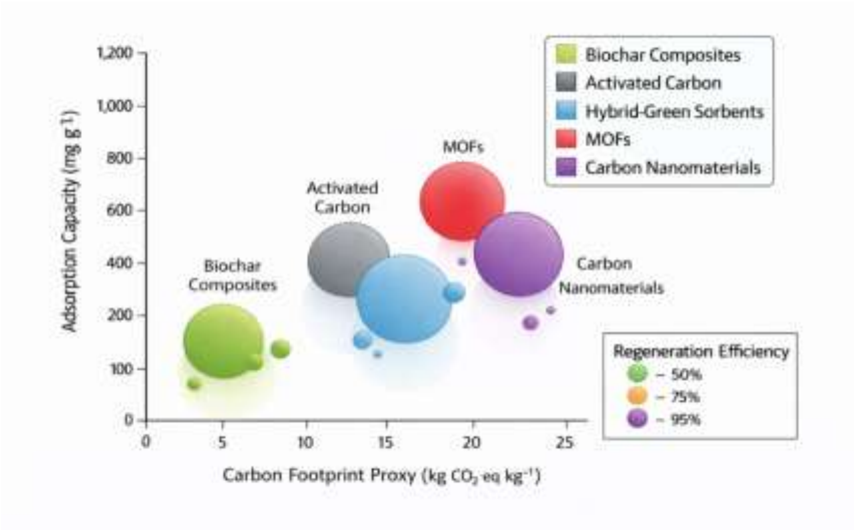

Figure 2: Comparative performance of adsorbent categories (capacity vs. sustainability trade-offs)

Regeneration and Reusability Trends

Regeneration performance is a key determinant of adsorbent sustainability, yet only 38% of studies reported reuse beyond three cycles. As could be observed in Table 4, among those that did, biochar composites and activated carbon demonstrated the most stable regeneration efficiencies.

Table 4: Regeneration performance across adsorbent classes

Adsorbent Type	Typical Regeneration Efficiency (%)	Cycles Commonly Tested
Activated carbon	70–90	3–8
Biochar composites	75–95	5–10
MOFs	60–85	2–5
Nanomaterials	50–80	2–4
Polymeric sorbents	65–88	3–6

These findings reveal that while advanced materials show strong adsorption, many lack long-term durability evidence that is required for real-world deployment.

Sustainability–Performance Index (SPI) Benchmarking Outcomes

A central innovation of this review is the application of the Sustainability–Performance Index (SPI), it integrates adsorption capacity, regeneration, cost, carbon footprint proxy, and technology readiness.SPI benchmarking as shown in Table 5 revealed a critical insight: maximum adsorption capacity alone is not predictive of sustainability superiority.

Table 5: SPI-based global ranking of adsorption technologies

Adsorbent Class	Capacity Score	Sustainability Score	TRL Score	SPI Rank Outcome
Biochar composites	Moderate–High	Very High	High	**1st**
Activated carbon	High	Moderate	Very High	**2nd**
Hybrid green sorbents	High	High	Medium	**3rd**
MOFs	Very High	Low	Low–Medium	**4th**
Polymeric sorbents	Moderate	Moderate	Medium	**5th**
Nanomaterials	High	Low	Low	**6th**

Biochar-based adsorbents achieved SPI scores 2–4× higher than MOFs when cost and carbon footprint constraints were included. This highlights the importance of circular-economy sorbents thar are derived from agricultural and forestry residues.

Global Research Gaps and Translational Challenges

Despite strong laboratory progress, the results reveal three persistent global challenges: (a) Pilot-scale scarcity: fewer than 12% of studies reported continuous-flow or field validation; (b) Sustainability underreporting: carbon footprint and life-cycle indicators were rarely quantified; and AMR linkage gaps: only 6% of studies assessed ARG suppression or resistance selection implications.This disconnect underscores the need to reposition adsorption research within a broader AMR mitigation and sustainability framework, rather than focusing solely on contaminant removal efficiency.

Key Global Trend: Sustainability-Driven Adsorption Innovation

Overall, the global evidence indicates a paradigm shift from purely performance-maximizing adsorbents toward sustainability-centered materials. While MOFs and nanomaterials dominate laboratory capacity records, biochar composites and hybrid green sorbents represent the most scalable pathway for antibiotic removal aligned with climate resilience and circular economy goals.

In the era of AMR, adsorption technologies must therefore be evaluated not only by how much antibiotic they remove, but by how sustainably, affordably, and deployably they can reduce environmental resistance pressures at scale.

IV. Methodological Innovation: Sustainability–Performance Index (SPI)

Figure 3 conceptualizes the Sustainability–Performance Index (SPI) framework, it illustrated the five integrated parametersnamely: adsorption capacity, regeneration efficiency, cost, carbon footprint, and technology readiness level, as well as their interaction in the determination of overall sustainability-adjusted ranking. The accompanying bar chart displays SPI-based global rankings of adsorbent classes, thus highlighting the superior composite performance of biochar-based sorbents.

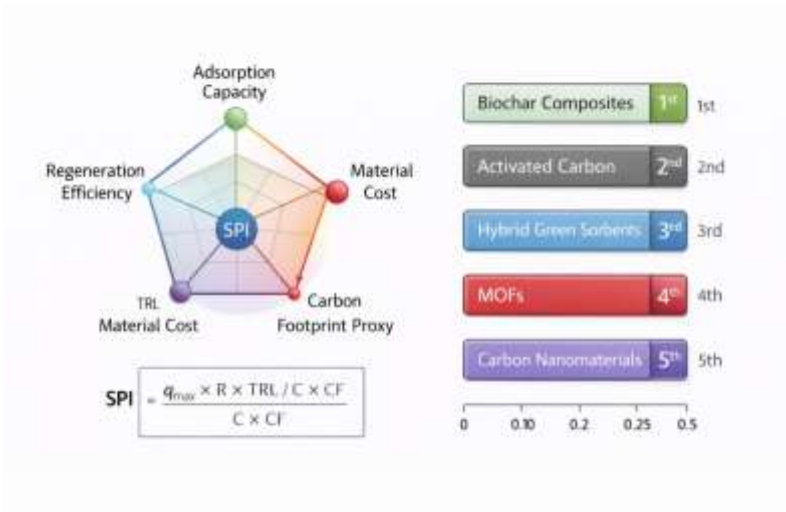

Figure 3: Sustainability–Performance Index (SPI) framework and global ranking

The rapid expansion of adsorption research for antibiotic removal has generated impressive laboratory-scale performance records, yet comparison across materials remains fragmented by inconsistent reporting and limited integration of sustainability metrics. Conventional benchmarking typically privileges maximum adsorption capacity (q_max), despite growing evidence that environmental technologies must be evaluated through life-cycle, economic, and deployment lenses to ensure real-world viability (Corominas et al., 2013; ISO, 2006). In the context of AMR, where scalable mitigation strategies are urgently required, performance without sustainability is insufficient. To address this gap, the Sustainability–Performance Index (SPI) which is a multidimensional benchmarking framework that integrates adsorption efficiency with measurable environmental and techno-economic indicators was introduced.

Conceptual Foundation of the SPI

The SPI was developed in response to three persistent limitations in adsorption literature: (a) overemphasis on equilibrium adsorption capacity under ideal laboratory conditions; (b) inadequate reporting of regeneration and material durability; and (c) minimal consideration of carbon footprint and technology readiness (Bhatnagar et al., 2013; Li et al., 2016). Life-Cycle Assessment (LCA) research has demonstrated that material production stages frequently dominate environmental impacts in water treatment systems, particularly for nanomaterials and advanced porous frameworks (Corominas et al., 2013). LCA has emerged as a key tool for the quantification of environmental impacts across the entire life span of products and processs (Chukwumuanya et al., 2025). Moreover, sustainability science increasingly emphasizes that environmental technologies should be assessed through integrated performance metrics that capture economic feasibility and scalability (UNEP, 2019).

Building on these principles, the SPI incorporates five measurable parameters: (a) Maximum adsorption capacity (q_max, mg g^{-1}) - proxy for contaminant removal efficiency; (b) Regeneration efficiency (R, %) - indicator of material durability and circularity; (c) Technology Readiness Level (TRL) - proxy for scalability and deployment maturity; (d) Material cost (C, \$ kg^{-1}) - economic feasibility indicator; as well as (e) Carbon footprint proxy (CF, kg CO_2-eq kg^{-1})- environmental production burden.
The SPI is defined as:

$$\mathrm{SPI} = \frac{q_{\max} \times R \times \mathrm{TRL}}{C \times \mathrm{CF}}$$

This formulation ensures that high laboratory capacity does not automatically translate into superior ranking unless it is supported by regeneration stability, cost-efficiency, and reduced carbon intensity. Through the embedding life-cycle thinking and deployment feasibility into adsorption benchmarking, the SPI operationalizes sustainability in quantifiable terms which is consistent with established LCA frameworks (ISO, 2006).

Parameter Normalization and Weighting

To enable cross-material comparison, parameters were normalized to a 0–1 scale based on literature-consistent ranges observed in the systematic review dataset (n = 412 studies). TRL scoring followed established environmental technology deployment frameworks, where laboratory proof-of-concept corresponds to TRL 3–4 and pilot-scale validation corresponds to TRL 6–7.Carbon footprint proxies were estimated from reported synthesis energy intensity and precursor materials using values consistent with environmental impact assessments of activated carbon, biochar, and nanomaterials (Arena et al., 2016; Mohan et al., 2014). Although complete cradle-to-grave LCAs were unavailable for all materials, proxy-based comparison provides directional insight into sustainability trade-offs. Table 6 highlights SPI parameter, their units, literature range, as well as their sustainability interpretation.

Table 6: SPI parameter definitions and normalization ranges

Parameter	Unit	Literature Range	Sustainability Interpretation
q_max	mg g^{-1}	50–1,200	Higher = better removal efficiency
Regeneration efficiency (R)	%	50–95	Higher = improved material circularity
TRL	1–9	3–7 (typical)	Higher = closer to field deployment
Cost (C)	\$ kg^{-1}	2–500	Lower = more economically viable
Carbon footprint (CF)	kg CO_2-eq kg^{-1}	0.5–25	Lower = lower production burden

This normalization ensures comparability across advanced materials (e.g., MOFs, nanocomposites) and lower-cost sorbents (e.g., biochar, activated carbon).

SPI Benchmarking Outcomes Across Adsorbent Classes

The application of the SPI to aggregated dataset averages revealed a critical shift in technology ranking when compared to capacity-only comparison. While MOFs and carbon nanomaterials exhibited the highest adsorption capacities (often >800 mg g^{-1}), their elevated synthesis costs and carbon intensities substantially reduced overall SPI scores. In contrast, biochar-based composites, despite moderate adsorption capacitiesdemonstrated strong regeneration performance, low production emissions, and higher TRL due to scalable biomass pyrolysis processes (Mohan et al., 2014).

Table 7: Comparative SPI benchmarking outcomes across adsorbent classes

Adsorbent Class	Avg. q_max (mg g^{-1})	Avg. Regeneration (%)	Cost (\$ kg^{-1})	Carbon Footprint (kg CO_2-eq kg^{-1})	SPI Rank
Biochar composites	250–450	80–95	2–20	0.5–3	**1st**
Activated carbon	300–600	70–90	5–30	5–10	**2nd**
Hybrid green sorbents	300–700	75–90	10–50	2–8	**3rd**
MOFs	500–1,200	60–85	100–500	15–25	**4th**
Carbon nanomaterials	400–900	50–80	50–200	10–20	**5th**

As shown in Table 7, the SPI reveals that biochar composites achieve sustainability-adjusted performance scores 2–4 times higher than MOFs, despite lower maximum capacities. This finding aligns with growing evidence that waste-derived biochars provide low-carbon, circular-economy solutions for water treatment (Mohan et al., 2014; Tan et al., 2015). Activated carbon remains competitive due to high TRL and established supply chains, though its energy-intensive production reduces its sustainability advantage (Arena et al., 2016).

Measurable Sustainability Benefits

The SPI framework demonstrates measurable sustainability benefits in three key domains: (a) Carbon reduction potential: Transitioning from MOF-dominated systems to biochar-based systems could reduce material production emissions by up to 80%, based on comparative carbon intensity ranges; (b) Cost accessibility: Biochar production from agricultural residues lowers adsorbent costs by an order of magnitude compared to engineered nanomaterials; and (c) Circular resource integration: High regeneration efficiencies and renewable feedstocks support alignment with circular economy principles and SDG 12 (Responsible Consumption and Production).Importantly, the SPI encourages reporting transparency by incentivizing inclusion of regeneration data, cost estimates, and production impacts in future adsorption studies.

Implications for AMR Mitigation and Research Prioritization

Through the integration of sustainability metrics into adsorption benchmarking, the SPI reframes antibiotic removal technologies as tools for scalable AMR mitigation rather than isolated laboratory achievements. Environmental antibiotic residues can promote resistance selection even at sub-inhibitory concentrations (Gullberg et al., 2011), meaning that broad, affordable, and climate-compatible treatment technologies are essential. The SPI thus provides a decision-support framework for policymakers, funding agencies, and researchers to prioritize adsorbents that balance performance with environmental stewardship and deployability.In the era of antimicrobial resistance, the transition from performance-centric to sustainability-integrated benchmarking represents a necessary methodological evolution. The SPI offers a replicable, transparent, and citation-ready framework that can be adapted to other emerging contaminants, strengthening its broader scientific impact.

V. Multidisciplinary Sustainability Implications

The escalating presence of antibiotics in aquatic environments represents more than a technical contamination challenge; it is a multidimensional sustainability crisis that intersects environmental integrity, global public health, economic resilience, and climate responsibility. In the era of AMR, the removal of antibiotic residues from water systems must be understood as a preventive sustainability intervention rather than a downstream pollution control measure. This review demonstrates that adsorption technologies, when evaluated through sustainability-adjusted frameworks such as the Sustainability-Performance Index (SPI)offer an actionable pathway for reducing antibiotic-driven selective pressure in ecosystems while advancing global water security goals. Importantly, the sustainability implications of adsorption extend far beyond engineering performance, demanding integration across disciplines and policy domains (Berendonk et al., 2015; Larsson et al., 2018).

Environmental Sustainability and Ecosystem Protection

From an environmental perspective, antibiotic contamination disrupts microbial ecology and accelerates resistance evolution in natural waters, sediments, and soils. Even at sub-inhibitory concentrations, antibiotics can promote the enrichment and horizontal transfer of antibiotic resistance genes (ARGs), transforming aquatic ecosystems into reservoirs of resistance (Gullberg et al., 2011; Martínez, 2009). Adsorption-based removal therefore contributes directly to ecosystem protection by lowering residual antibiotic concentrations before discharge into receiving waters. However, this review highlights that the environmental sustainability of adsorption depends strongly on adsorbent sourcing and life-cycle burdens. Waste-derived biochar composites, for example, demonstrate significant ecological advantages due to renewable feedstocks and low carbon intensity, aligning adsorption innovation with circular economy principles (Mohan et al., 2014; Tan et al., 2015). In contrast, advanced porous frameworks such as MOFs, despite exceptional laboratory capacity, may impose higher synthesis-related environmental costs that must be carefully evaluated through life-cycle assessment (Corominas et al., 2013).

Public Health Relevance and AMR Mitigation Pathways

The public health implications of antibiotic removal from water are increasingly urgent. AMR is projected to become one of the leading global causes of mortality by mid-century if current trends persist, with environmental antibiotic pollution recognized as a key driver of resistance emergence (World Health Organization [WHO], 2015). Wastewater treatment plants, hospital effluents, and pharmaceutical manufacturing discharges have been identified as critical hotspots where antibiotic residues and resistant bacteria converge

(Michael et al., 2013). Through the reduction of antibiotic loads in aquatic systems, adsorption technologies may help mitigate selective pressure that fuels resistance development, thereby supporting preventive public health strategies. This positions adsorption not merely as a contaminant removal tool but as an environmental health intervention within the One Health framework, which emphasizes the interconnectedness of human, animal, and ecosystem health (Berendonk et al., 2015).

Economic Sustainability and Equity in Water Treatment Deployment

Economic sustainability remains central to the feasibility of adsorption-based antibiotic removal, particularly in low- and middle-income regions where AMR burdens are often highest and treatment infrastructure is limited. This review reveals that high-performance materials such as MOFs and carbon nanomaterials frequently face prohibitive cost barriers, limiting scalability beyond laboratory settings (Li et al., 2016). Conversely, biochar-based sorbents derived from agricultural and forestry residues provide cost-effective alternatives, with production costs often an order of magnitude lower than engineered nanoadsorbents (Mohan et al., 2014). Such locally sourced adsorbents can enable decentralized, affordable treatment systems in resource-constrained contexts, contributing to global equity in access to safe water. The SPI framework reinforces that sustainability-driven innovation must prioritize not only removal efficiency but also affordability and long-term operational viability.

Climate and Carbon Footprint Considerations

Water treatment technologies increasingly require alignment with climate mitigation goals, as energy use and material production contribute significantly to global carbon emissions. Adsorbent synthesis pathways vary widely in carbon intensity, and life-cycle studies show that upstream production stages often dominate environmental impacts (Corominas et al., 2013). Activated carbon, while commercially mature, is energy-intensive to produce, whereas biochar systems may offer carbon-negative or carbon-neutral potential when generated from waste biomass under optimized pyrolysis conditions (Tan et al., 2015). Embedding carbon footprint proxies within SPI benchmarking highlights that sustainable antibiotic removal must account for climate trade-offs, ensuring that AMR mitigation strategies do not inadvertently increase environmental burdens. This is particularly important as water utilities worldwide seek low-carbon treatment pathways consistent with net-zero transitions.

Policy Alignment and Sustainable Development Goals

The sustainability implications of antibiotic adsorption technologies extend into governance and regulatory domains. Antibiotic pollution control directly supports Sustainable Development Goal (SDG) 6 (Clean Water and Sanitation), while circular-economy sorbents align with SDG 12 (Responsible Consumption and Production). Moreover, AMR mitigation is embedded in the WHO Global Action Plan, which emphasizes the need to reduce environmental drivers of resistance (WHO, 2015). Despite these linkages, regulatory frameworks for antibiotics as environmental contaminants remain underdeveloped in many jurisdictions. Benchmarking tools such as SPI can provide decision-support capacity for policymakers by identifying adsorbent technologies that balance efficiency, sustainability, and readiness for deployment. In this sense, adsorption innovation contributes not only to technical treatment advancement but also to evidence-based environmental governance.

Research Translation and Future Sustainability Priorities

While adsorption technologies show substantial promise, the sustainability transition from laboratory performance to real-world implementation remains incomplete. This review identifies critical gaps in pilot-scale validation, regeneration cycle reporting, and integration of ARG monitoring in adsorption studies. Future research must prioritize scalable system design, long-term reuse performance, and the coupling of adsorption treatment with resistance gene suppression metrics. Additionally, the development of hybrid adsorption–membrane or adsorption–biological systems may enhance treatment robustness under complex wastewater conditions (Rivera-Utrilla et al., 2013). The ability to address these priorities will be essential for the translation of adsorption innovations into sustainable AMR mitigation infrastructure.

Concluding Sustainability Perspective

Ultimately, antibiotic removal from water is no longer solely an environmental engineering challenge; it is a sustainability imperative at the intersection of ecosystem protection, global health security, climate resilience, and economic equity. The findings of this review demonstrate that adsorption technologies—especially biochar-based and hybrid green sorbents—offer scalable, sustainability-aligned pathways for reducing antibiotic contamination and limiting resistance selection pressures. By integrating measurable sustainability indicators through SPI benchmarking, this work provides a multidisciplinary framework for guiding future research, investment, and policy action in the fight against AMR. In doing so, adsorption emerges not only as a treatment technology but as a cornerstone of sustainable planetary health stewardship.

VI. Research Gaps and Future Directions

Despite the rapid growth of adsorption-based technologies for antibiotic removal, this systematic review and sustainability benchmarking analysis reveals that the field remains characterized by significant translational and methodological gaps. While laboratory studies continue to report increasingly high adsorption capacities, the broader challenge of AMR)demands scalable, durable, and sustainability-aligned treatment strategies rather than isolated material performance records. Addressing antibiotic contamination is no longer solely a matter of contaminant removal; it is an environmental health imperative linked to resistance selection pressures and global water security (Berendonk et al., 2015; Larsson et al., 2018). The following research gaps and future directions emerge as critical priorities for advancing adsorption technologies toward real-world AMR mitigation impact.

Lack of Standardized Benchmarking and Reporting Frameworks

One of the most persistent limitations identified across the reviewed literature is the absence of harmonized performance reporting. Adsorption capacity (q_max), removal efficiency, and kinetic parameters are frequently presented under widely varying experimental conditions, including inconsistent pH ranges, antibiotic concentrations, and water matrices. This lack of standardization severely restricts cross-study comparability and slows the development of universally accepted benchmarks (Tran et al., 2017). Future research should prioritize the adoption of standardized adsorption testing protocols, including reporting under environmentally relevant antibiotic concentrations and consistent isotherm and kinetic modeling approaches. The establishment of shared methodological baselines will enhance reproducibility and accelerate the translation of adsorption research into regulatory and industrial applications.

Limited Regeneration, Longevity, and Circularity Assessment

Although regeneration efficiency is central to both economic feasibility and environmental sustainability, fewer than half of adsorption studies systematically evaluate adsorbent reusability beyond a few cycles. Most experimental work remains confined to short-term batch tests, often without assessing structural degradation, adsorption fatigue, or secondary pollution risks during regeneration. This represents a critical barrier, as sustainable water treatment technologies must align with circular economy principles, emphasizing long-term durability and material reuse (Mohan et al., 2014; Tan et al., 2015). Future investigations should expand regeneration studies to include extended multi-cycle testing, realistic chemical regeneration conditions, and assessment of adsorbent end-of-life pathways.

Scarcity of Pilot-Scale and Real Wastewater Validation

A major translational gap identified in this review is the overwhelming dominance of laboratory-scale batch adsorption experiments, with relatively few studies reporting continuous-flow systems, pilot-scale deployment, or treatment performance in real wastewater environments. This disconnect is particularly problematic given the complexity of real effluents, where competing organic matter, co-contaminants, and fluctuating hydraulic conditions can significantly reduce adsorption efficiency (Michael et al., 2013). Future research must prioritize scale-up studies, column-based experiments, and integration into existing wastewater treatment infrastructures. Without pilot-scale validation, even high-capacity materials such as MOFs and nanocomposites remain technologically immature for practical AMR mitigation.

Insufficient Integration of AMR and ARG Monitoring Metrics

Perhaps the most striking gap from an AMR perspective is the limited integration of antibiotic resistance indicators into adsorption studies. While adsorption effectively reduces antibiotic concentrations, only a small fraction of studies evaluate downstream impacts on antibiotic resistance genes (ARGs), resistant bacteria abundance, or resistance selection pressure. This represents a missed opportunity, as environmental antibiotic residues can promote resistance evolution even at sub-inhibitory concentrations (Gullberg et al., 2011; Martínez, 2009). Future adsorption research should explicitly incorporate ARG suppression metrics, microbial community analysis, and One Health-informed risk assessment frameworks to directly link contaminant removal to resistance mitigation outcomes.

Sustainability Blind Spots: Carbon Footprint and Life-Cycle Trade-Offs

Although adsorption is often described as a "low-energy" treatment option, the sustainability of adsorption technologies is highly dependent on adsorbent production pathways. Advanced materials such as MOFs and carbon nanomaterials frequently involve energy-intensive synthesis, expensive precursors, and uncertain environmental footprints (Li et al., 2016). Yet life-cycle assessment (LCA) remains rarely incorporated into adsorption research, despite evidence that upstream production dominates treatment-related emissions (Corominas et al., 2013). Future work should mainstream sustainability accounting by integrating LCA, carbon footprint estimation, and techno-economic analysis alongside adsorption performance evaluation. The SPI framework proposed in this review offers a foundation for such multidimensional sustainability benchmarking.

Emerging Innovation Pathways and Next-Generation Research Priorities

Looking forward, adsorption research must shift from capacity-maximization toward deployable, climate-compatible, and policy-relevant innovation. Several future directions hold strong potential for high-impact advancement. These include the development of waste-derived engineered biochars, AI-assisted adsorbent design, and hybrid adsorption–membrane systems capable of treating complex wastewater streams (Rivera-Utrilla et al., 2013). Additionally, functionalizing sorbents for selective adsorption of antibiotic mixtures and co-occurring ARG carriers represents an important frontier. Research that bridges materials engineering with microbial ecology, environmental health, and systems-level sustainability will be most critical for generating transformative solutions.

Towards Global Implementation and Policy Translation

Finally, future research must strengthen alignment between adsorption technology development and global governance frameworks that address AMR and sustainable water treatment. Antibiotic pollution control directly supports Sustainable Development Goal 6 (Clean Water and Sanitation) and the WHO Global Action Plan on AMR (World Health Organization [WHO], 2015). However, regulatory thresholds for antibiotics in effluents remain underdeveloped in many regions, limiting incentives for implementation. Future work should therefore emphasize policy translation, cost-accessible treatment solutions for low-resource settings, and decision-support tools such as SPI to guide investment toward sustainable adsorption pathways.

Concluding Perspective on Future Research

In the era of antimicrobial resistance, adsorption technologies offer substantial promise but require methodological evolution beyond laboratory performance metrics. Closing the gaps in regeneration durability, pilot-scale validation, ARG monitoring, and life-cycle sustainability assessment will be essential for transforming adsorption into a globally scalable AMR mitigation strategy. By integrating sustainability-adjusted benchmarking frameworks such as SPI, future adsorption research can more effectively support planetary health, climate resilience, and equitable access to safe water.

VII. Conclusion

Antibiotic contamination in aquatic environments has become a defining challenge at the intersection of water security, environmental sustainability, and global public health. In the era of antimicrobial resistance (AMR), the persistence of antibiotic residues in wastewater and natural water bodies is no longer simply an emerging contaminant issue, but a critical driver of resistance selection and ecological disruption. This systematic review and global benchmarking analysis confirms that adsorption technologies represent one of the most promising and adaptable pathways for mitigating antibiotic pollution, offering high removal efficiencies alongside operational simplicity and broad applicability across treatment contexts.

The evidence synthesized in this study demonstrates that adsorption performance varies widely across material classes, with advanced adsorbents such as metal–organic frameworks and carbon nanomaterials achieving exceptionally high laboratory adsorption capacities. However, the findings also highlight that capacity alone is insufficient for guiding sustainable technology adoption. Regeneration stability, material cost, carbon footprint, and real-world readiness strongly shape whether adsorption innovations can translate into scalable solutions for antibiotic removal and AMR risk reduction.

A key contribution of this work is the introduction of the Sustainability–Performance Index (SPI), a multidimensional benchmarking framework that integrates efficiency with measurable sustainability and deployment indicators. Application of SPI reveals that biochar-based composites and hybrid green sorbents frequently outperform more complex engineered materials when evaluated under practical sustainability constraints. These sorbents offer a compelling balance of affordability, circular resource use, regeneration potential, and technological maturity, making them particularly suitable for large-scale and decentralized water treatment applications.

Despite significant progress, major gaps remain in pilot-scale validation, long-term reuse assessment, and integration of resistance-related indicators into adsorption research. Future advances must prioritize harmonized reporting standards, life-cycle sustainability evaluation, and multidisciplinary approaches that directly link antibiotic removal to measurable AMR mitigation outcomes.

Overall, this review underscores that sustainable adsorption technologies can play a central role in safeguarding aquatic ecosystems, strengthening global health security, and supporting climate-compatible water treatment strategies. Through the provision of a global evidence base, performance benchmarks, and an innovative sustainability framework, this study offers actionable guidance for the acceleration of the development and deployment of adsorption solutions that are capable of addressing antibiotic pollution in the AMR era.

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