REVIEW ARTICLE **DOI: 10.sjas. 202510060002**

Advances in Polysaccharide-Based Aerogels for Water Treatment: A Metadata-Analysis of Adsorption Performance

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Cite this Article: Shahzadi I (2026). Advances in Polysaccharide-Based Aerogels for Water Treatment: A Metadata-Analysis of Adsorption Performance. SciNex Journal of Advanced Sciences. 01 (02): 202510060002

ABSTRACT: Environmental pollution, particularly from heavy metals, poses a significant threat to ecosystems and human health. Industrial and agricultural activities contribute to water contamination, necessitating innovative and sustainable remediation strategies. Biomass-derived materials offer a promising approach for pollutant removal, aligning with circular bioeconomy principles. Among these, polysaccharide-based aerogels have gained attention due to their high porosity, large surface area, and functional versatility. These bio-based materials, particularly yeast and chitosan-derived aerogels, exhibit excellent adsorption capacity for heavy metal ions and dyes, providing an eco-friendly alternative to conventional wastewater treatment methods. This review explores the sources and impacts of heavy metal pollution, evaluates existing wastewater treatment technologies, and highlights the role of polysaccharide-based aerogels as efficient adsorbents. By leveraging the unique properties of these materials, such as biodegradability, renewability, and surface functionalization, aerogels can serve as a viable solution for heavy metal remediation. Future research should focus on optimizing aerogel formulations, improving recyclability, and scaling up production for practical applications in wastewater treatment.

KEYWORDS: Biomass aerogels; Polysaccharides; Yeast; Chitosan; Heavy metal removal; Adsorption; Wastewater treatment.

INTRODUCTION

Water Sources and Consumption

Water, existing naturally in solid, liquid, and gaseous states, resides in diverse locations like the atmosphere, oceans, Earth's surface, and beneath it. Groundwater and surface water, critical for municipal, industrial, and agricultural needs, vary based on geomorphology, climate, and land use (Khodakarami and Bagheri, 2021). The global water distribution is illustrated in Figure 1. As the global population expands and water demands intensify, groundwater, a pivotal source of fresh water, is being depleted faster than it can replenish. Surface water, constituting only 1 percent of total fresh water, is vulnerable to pollution from both human activities and natural processes. Agricultural runoff, industrial discharges, and urban wastewater contribute pollutants that detrimentally impact water quality. Figure 2 depicts water consumption and wastewater production across major sectors. The United Nations World Water Development Report (2017) reveals that 56 percent of withdrawn freshwater for municipal, industrial, and agricultural use is discharged as untreated wastewater. Shockingly, 80% of globally generated wastewater is released into the environment without adequate treatment, and in certain developing nations, an alarming 95 percent of wastewater returns to ecosystems without undergoing any treatment (UNESCO et al., 2017). As reported by the 2023 UN World Water Development Report, a striking 26% of the global population, approximately 2 billion people, faced inadequate access to safely managed drinking water services (UNESCO, 2023). This encompasses 1.2 billion individuals with only basic services, 282 million with limited access, 367 million relying on treated sources, and 122 million compelled to use unsafe surface water. This critical challenge is exacerbated by the contamination of freshwater sources with heavy metal ions further intensifying the crisis. Thus, heavy metal contamination not only threatens drinking water security but also amplifies the urgency for sustainable and efficient remediation technologies.

Wastewater Pollution

Wastewater pollution is a significant environmental problem caused by human activities and increased industrialization. Currently, the situation involves a widespread influx of various harmful substances, such as organic compounds and heavy metals, into water systems. Heavy metals, in particular, pose a serious threat to both the environment and human health (Wei et al., 2022). Releasing untreated wastewater without proper treatment not only harms the biodiversity of water bodies but also disrupts the balance of ecosystems. It is crucial to address wastewater pollution urgently due to its negative impact on water quality, aquatic life, and human well-being. Therefore, it is essential to develop effective wastewater treatment methods to minimize the harmful effects of pollution and promote a balanced relationship between human activities and the aquatic environment. The term 'heavy metal' is generally reserved for metals whose density exceeds 5 gcm^{-3} (Razzak et al., 2022). However, in an ecological sense, any metalloid can be classed as a heavy metal (Laureano-Anzaldo et al., 2021). Human exposure to heavy metals has also risen dramatically due to an exponential increase in their usage in several industrial, agricultural, domestic, and technological applications. Among the numerous pollutants present in wastewater, heavy metals stand out due to their persistence, bioaccumulative potential, and toxicity across ecological and human systems.

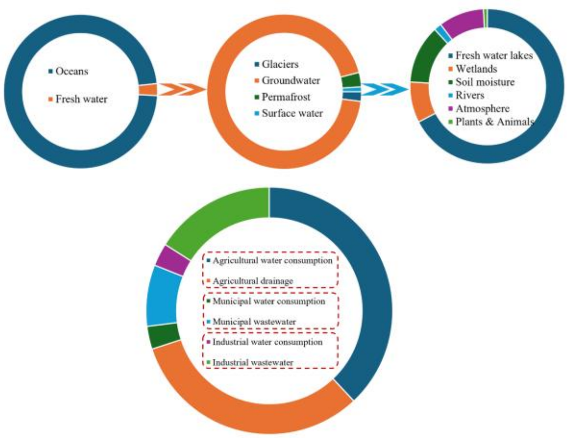

Figure 1: The worldwide distribution of water resources, along with the consumption of water and production of wastewater by major sectors (UNESCO et al., 2017).

Heavy Metals Sources and Impacts

Heavy metal pollution is one of the important issues in China due to economic and industrial developments (Rajeshkumar et al., 2018a). Heavy metals, such as lead, cadmium, copper, and chromium, are particularly concerning pollutants. They are non-biodegradable and can accumulate in the environment, leading to bioaccumulation in the food chain. Their presence in water bodies can cause severe problems, including toxicity to aquatic life and humans (Wang et al., 2020; Li et al., 2023; Sun et al., 2023b).

Importance of Wastewater Treatment

Given the shortcomings of conventional methods, researchers have increasingly explored adsorption-based strategies, which offer unique advantages in terms of efficiency, versatility, and cost-effectiveness.

Wastewater Treatment

The treatment of wastewater is crucial for protecting water resources and maintaining ecological balance. It plays a pivotal role in safeguarding human health by mitigating the detrimental effects of heavy metal pollutants. The methods for heavy metal removal from wastewater are of diverse types with highly variable mechanisms, nature of materials and functional properties. Each method has its specific spectrum of merits and demerits defining its appropriateness to be practiced under given circumstances. The most widely conventional water treatment techniques for the pollutants are ion exchange, reverse osmosis, electro-precipitation, coagulation/flocculation, sedimentation, flotation, adsorption, oxidation, membrane separation and advanced oxidation process (Kanani-Jazi and Akbari, 2024).

Chemical Precipitation involves adding chemicals to wastewater to form insoluble precipitates with heavy metals, which are then removed. While effective for large-scale operations, it generates sludge and may not be efficient for low concentrations of metals. Electrocoagulation, though exhibiting variable cost-effectiveness, is notable for heavy metal removal, necessitating trained operators for optimal performance. Membrane technologies, such as reverse osmosis, offer efficient removal but come with higher energy requirements and costs, requiring trained personnel for both operation and maintenance (Qasem et al., 2021). Precipitation and coagulation-flocculation methods are viable for heavy metal removal, with moderate energy usage and cost-effectiveness, and they typically require basic training for implementation. Each of these technologies has its own advantages and disadvantages.

Moreover, these technologies have not reached all parts of the globe, only a few developed and developing countries are using them (Singh et al., 2018). All of these technologies have long lists of associated merits and demerits because none of the techniques fully comply with the above-mentioned characteristic features. All these heavy metal removal techniques are evolving due to continuous efforts of the researchers in the relevant fields. All of these methods (heavy metal removal techniques) have been assisted by incorporation of different materials and their performance have been evaluated against different metals of human interest. However, their adoption is prioritized based on their operational costs. Developed countries can afford most of these techniques, but developing countries need to synchronize many factors to make them feasible. Most of the researchers recommended using locally available materials for heavy metal removal activities that do not require expensive modifications. Therefore, heavy metal-removing technologies have always been under extensive debate and continuous evolution. Although researchers have made great efforts and significant achievements, there is still a large gap in finding an ideal technique for heavy metal removal from water.

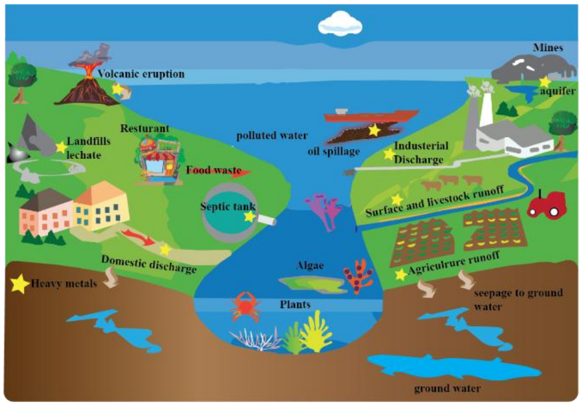

Figure 2: Sources and transportation of heavy metals into environmental system.

Wastewater Treatment Through Adsorption

The most general definition describes adsorption as an enrichment of chemical species from a fluid phase on the surface of a liquid or a solid. The main advantages of the sorption technique include its effectiveness over a wide range of metal concentrations and the simplicity of its application (Singh et al., 2018). Typical adsorption process has been displayed in Figure 3.

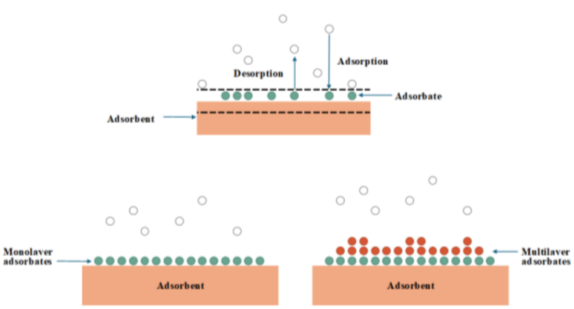

Figure 3: Schematic representation of adsorption process with monolayer and multilayered adsorption phenomena.

METHODS

This study employed a metadata-analysis approach to synthesize evidence from previously published research on polysaccharide-based adsorbents for water treatment, with particular emphasis on aerogels derived from biomass sources such as yeast and chitosan. To ensure comprehensive coverage, literature searches were conducted across multiple scientific databases including Web of Science, Scopus, PubMed, and Google Scholar. The search strategy combined key terms such as "polysaccharide aerogels," "biomass adsorbents," "chitosan-based aerogels," "yeast aerogels," "water treatment," "heavy metal removal," and "adsorption capacity." Only peer-reviewed articles, published in English up to August 2025, were considered. Additional references were retrieved from the bibliographies of relevant reviews and research articles to minimize the likelihood of omitting important studies.

Data Selection

The selection process followed a two-step screening protocol. First, titles and abstracts were reviewed to exclude studies irrelevant to adsorption or those not focused on water purification. Second, full-text evaluation was performed to determine eligibility based on predefined criteria. Studies were included if they reported experimental data on polysaccharide-derived aerogels or related bio-based adsorbents, and provided quantitative measures of adsorption performance such as maximum adsorption capacity (qmax), adsorption kinetics, equilibrium models, regeneration efficiency, or comparative performance with conventional adsorbents. Exclusion criteria comprised studies without sufficient experimental detail, papers focused purely on material synthesis without adsorption assessment, or works unrelated to water treatment applications.

Metadata Analysis

For each included article, relevant metadata were extracted systematically. These included details of the adsorbent material (type of polysaccharide, crosslinking or modification methods, structural characteristics such as porosity and surface area), target pollutants (heavy metals, dyes, or mixed contaminants), experimental conditions (pH, temperature, contact time, initial concentration), and reported adsorption outcomes. Where available, regeneration cycles and reusability data were also documented to evaluate sustainability. The extracted information was organized into a comparative database that enabled both qualitative synthesis and quantitative analysis.

Bibliometric Mapping

To visualize research evolution, a bibliometric analysis was performed using VOSviewer and CiteSpace. Keyword co-occurrence, citation frequencies, and annual publication trends were analyzed to highlight shifts in thematic focus (e.g., from synthetic polymers to bio-based aerogels). This metadata analysis allowed identification of high-impact keywords, research clusters, and publication peaks over the last two decades.

Quality Assurance

To reduce bias, multiple reviewers cross-checked article selection and data extraction. Discrepancies were resolved by consensus. When performance values varied widely, median values or ranges were reported. To harmonize data across studies, adsorption performance values were normalized to standard units (mg g^{-1}) and categorized by pollutant class. Descriptive statistics were used to identify trends in adsorption efficiency among different material types, while comparative assessments highlighted the influence of aerogel structure, surface functionalization, and synthesis method on removal efficiency. Emphasis was placed on identifying knowledge gaps, recurring limitations, and future research

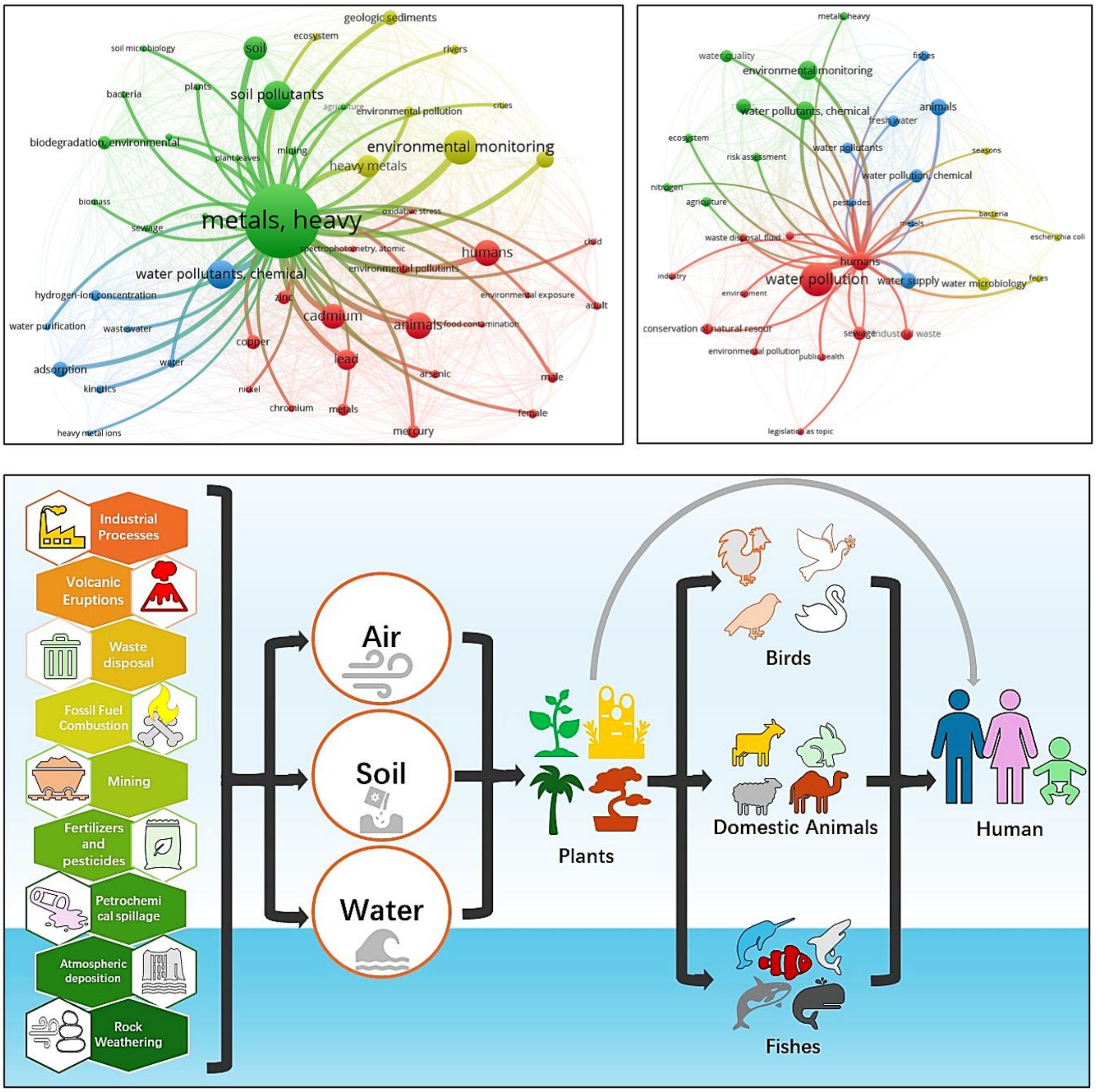

Figure 4: Bibliometric analysis-based interlinkages of environmental factors and transportation of heavy metals inside ecosystem impacting environment.

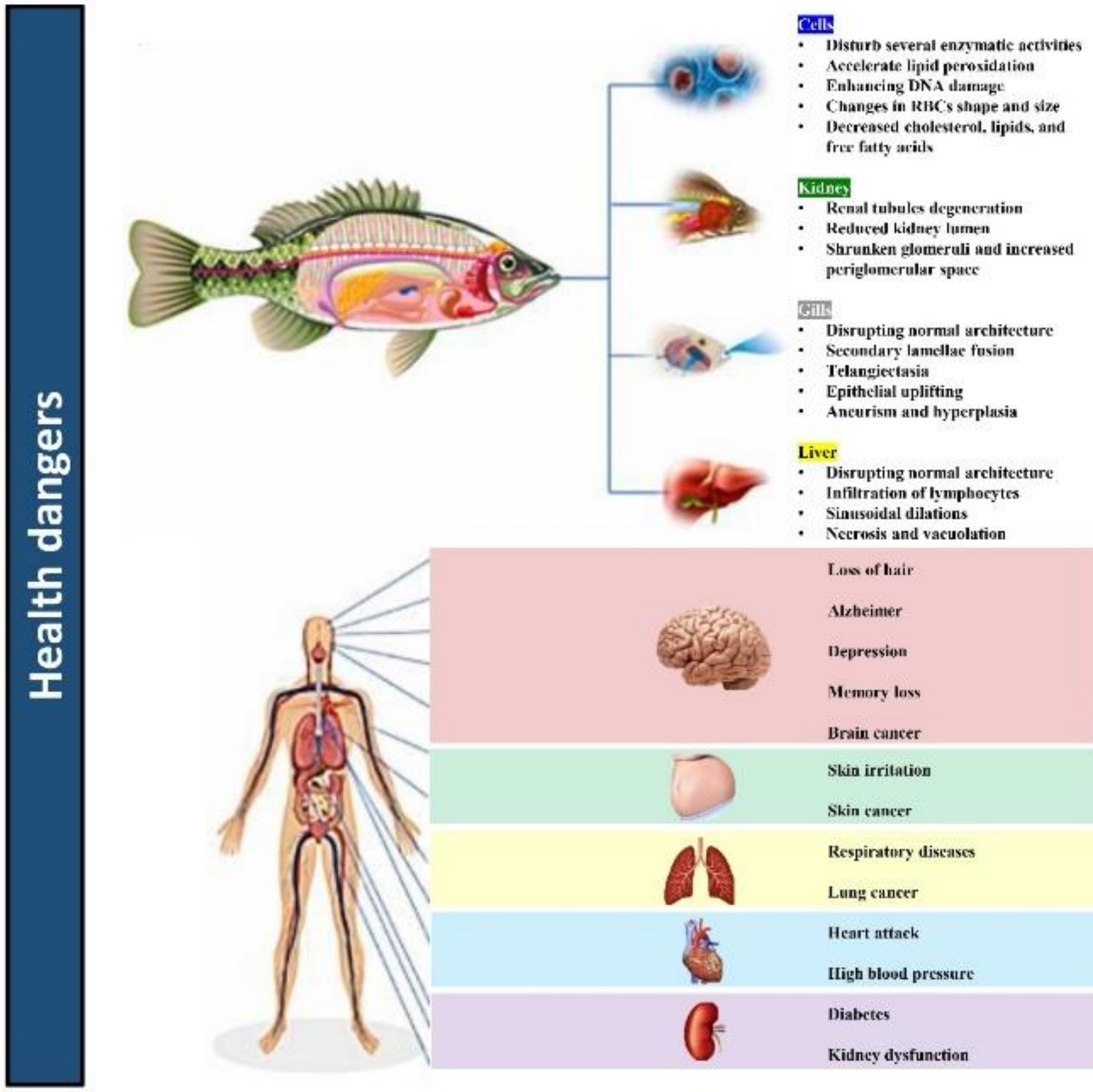

Figure 5: Impact of wastewater contaminated with toxic chemicals on aquatic flora such as fish and the various diseases associated with them; the impact of heavy metals on humans.

directions. No new experimental work was conducted as this study relied exclusively on previously published literature.

RESULTS AND DISCUSSION

The literature analysis based on relevant keywords concluded that anthropogenic factors, such as industrial discharges and agricultural practices, significantly (Figure 4) amplified the complexity of these interactions, exacerbating environmental repercussions. Heavy metals contamination possesses serious implications for aquatic ecosystems and human health. The gravity of the issue is underscored by the persistent and cumulative nature of heavy metals, leading to long-term ecological repercussions. Heavy metal pollution is a multifaceted environmental challenge influenced by a myriad of parameters. The foremost contributors encompass pH levels, organic matter content, and redox potential of soil and water systems (Hou et al., 2020). These parameters intricately influence metal speciation, solubility, and adsorption, thereby dictating their bioavailability. Temperature and microbial activity further modulate these interactions, underscoring the dynamic nature of heavy metal pollution in the environment (Zhao et al., 2023). Water bodies serve as reservoirs for metal accumulation. Besides acting as a significant sink for metal deposition these sediments subsequently re-release heavy metals into the water column under varying physical and chemical conditions (Rajeshkumar et al., 2018b). The intricate interplay of these environmental factors contributes to the persistence and widespread distribution of heavy metals, amplifying their adverse effects on aquatic biota and human populations dependent on contaminated water sources.

impacting their mobility and bioavailability. Plants serve as primary receptors, accumulating metals from the water or soil through intricate uptake mechanisms (Ahmad et al., 2021; Xu et al., 2022a; Haddad et al., 2023). Subsequently, herbivores and omnivores assimilate these metals by consuming contaminated plant material. The bioaccumulation phenomenon intensifies as metals traverse through trophic levels, culminating in potential health risks for apex predators,

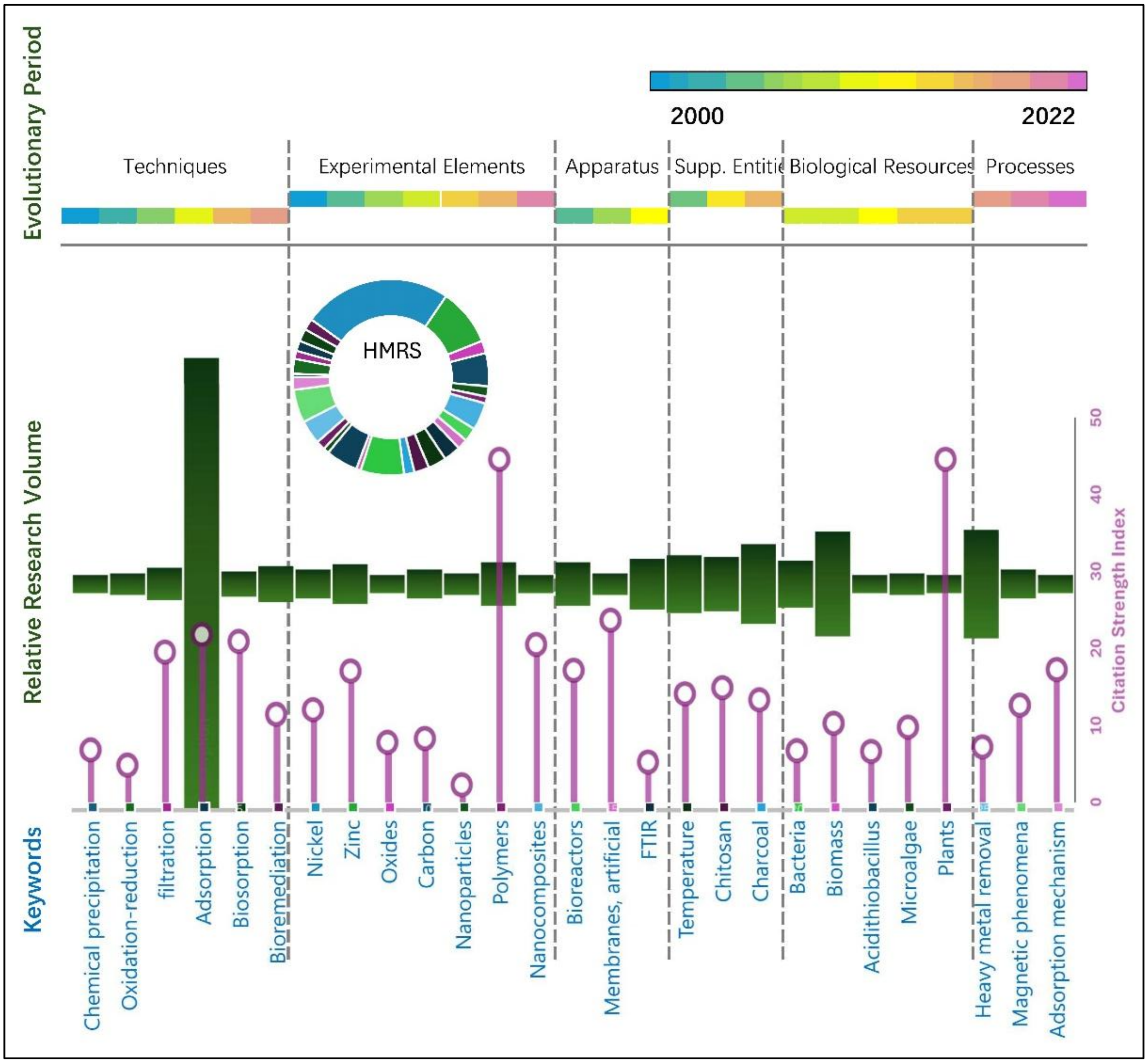

Figure 6: Time-course metadata analysis of heavy metal removal studies exploiting different research techniques and components.

The journey of heavy metals within the ecological continuum is an intricate cascade involving distinct phases. Initiated by anthropogenic activities, metals are discharged into the environment through industrial effluents, agricultural runoff, and atmospheric deposition. Upon introduction, these metals undergo dynamic transformations in soil and water matrices, including humans.

Furthermore, consumption of a toxic diet by fish from a heavy metals laden environment posse adverse effects on humans (Huang et al., 2015; Noman et al., 2022). This is because heavy metals toxicity can cause energy depletion and damage to the brain, lungs, kidneys, liver, blood and other vital organs (Figure 5). In the long term, high exposure can lead to physical, tissue and neurological degeneration, reproducing diseases such as Parkinson's, muscular dystrophy, and multiple sclerosis.

Evolutionary Analysis of Materials for Adsorption

Among all heavy metal removal techniques, adsorption is one of the processes that stands out due to its high efficiency, easy handling, and wide adaptability (Chai et al., 2021; Song et al., 2021; Tamjidi et al., 2021). Adsorption, a physicochemical phenomenon where solute molecules form a thin film on a solid surface, is widely utilized for heavy metal removal from water. This technique offers numerous advantages such as eco-friendliness, abundant materials for adsorbents, low processing costs, easy fabrication methods, regeneration capability, and the ability to remove trace concentrations of pollutants (Ihsanullah et al., 2022). Although preparing adsorbents is not economical, the technique is still ranked among the top water treatment technologies. A number of researchers to develop adsorbents with improved characteristic features, and their efforts have sub-categorized the technique based on the type of adsorbents being used (Mariana et al., 2021; Natrayan et al., 2022).

Adsorption has emerged as the most popular technique with respect to published articles of the last two decades, for which the maximum manuscripts have been published in 2015. However, the mechanism of adsorption is a neophyte among research topics with maximum publications recorded during 2022. The keywords 'biomass' received the maximum citations score among all the keywords co-occurred with 'heavy metal removal' (Figure 6).

Due to demographic expansion and technological progression the use of petroleum-derived adsorbents has been significantly amplified (Gilbert, 2017). The annual yield of synthetic polymers has witnessed a substantial surge, escalating from 1.5 million metric tons in 1950 to 359.0 million metric tons in 2018 (Shanmugam et al., 2020; Elgarahy et al., 2023). These synthetic constituents pose severe environmental threats and adversely affect human life by generating hazardous waste that detrimentally impacts terrestrial, aquatic, and atmospheric ecosystems. Regrettably, the primary concerns associated with the manufacturing processes of these non-biodegradable synthetic polymers are the emission of greenhouse gases. To mitigate these potentially lethal challenges, it is imperative to devise and implement prospective solutions for environmental preservation. Over the past few decades, there has been a burgeoning interest in bio-based materials derived from naturally renewable resources and eco-friendly products which are anticipated to play a pivotal role in superseding synthetic materials (George et al., 2020; Kartik et al., 2021). Biowaste is an important component, and its production is expected to expand considerably each year, with 100 billion metric tons of biowaste generated annually in the world (Xu et al., 2022b). Biowaste, notable for its biodegradability and transformability, largely stems from industrial and agricultural operations, municipal works, and daily life activities. It is predominantly made up of agricultural residues, industrial, and food waste. Typically, biowaste is known for its complex composition, high yield, and abundant organic matter, which can be broken down by microorganisms (Hameed et al., 2021; Guo et al., 2022). Therefore, comprehensive utilization of biowaste is essential. Hence recycling biowastes from agriculture, food and beverage industries is an important aspect of waste management (Figure 7).

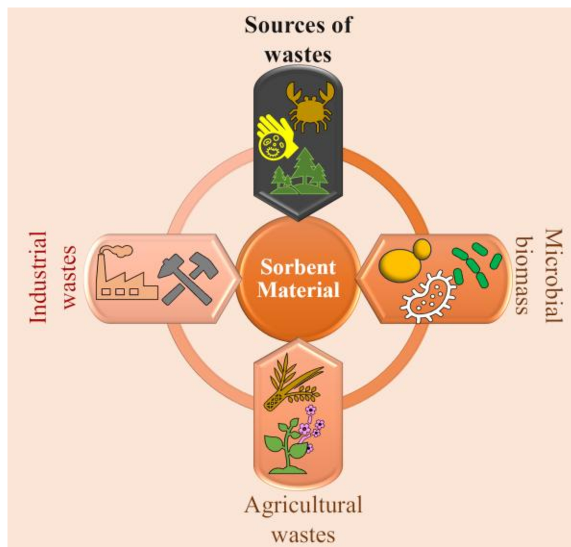

Figure 7: Origins and categorization of biomass waste that could potentially serve as adsorbents.

Therefore, alternative technologies must be considered to convert biowaste into valuable resources, indicating a transition to the concept of 'reuse and recovery'. These are the carbon containing biowastes and their reuse has got enormous attention due to growing energy and environmental issues (Chilakamarry et al., 2022; Xu et al., 2022c). In fact, compared with the petroleum resources, biowastes are comprised of higher oxygen and nitrogen contents and lower percentages of hydrogen and carbon due to which they can produce more chemicals than petrochemicals. Hence it is a proven fact that biowastes are a highly precious resource and our little efforts on developing high value-added products from biowastes can reduce our dependence on petroleum resources and can solve the environmental problems.

Furthermore, it will also significantly reduce our costs on the development of such high value-added products, greatly improving the economic efficiency (Ranjbari et al., 2022).

Identification and assessment of efficient low-cost adsorbents with high metal-binding capacities has attracted much attention in present era. Bio-wastes have recently gained attention as potential adsorbents due to their cost efficiency, environmental friendliness, and distinctive characteristics (Qiu et al., 2020). Importantly, microorganisms (bacteria, yeasts, and algae etc.) have been widely utilized for the adsorption of various contaminants, including heavy metals (Vishan et al., 2019; Mosai et al., 2020a), dyes (Xia et al., 2019) and mycotoxins (Ge et al., 2017). Microorganisms have a high surface area-to-volume ratio owing to their small size and therefore, they can provide a large contact interface which could interact with metals from the surrounding environment (Peng et al., 2010).

Yeast Biomass: Yeast biomass, particularly Saccharomyces cerevisiae, are frequently suggested as effective sources of adsorbent material due to numerous benefits. These include their ease of cultivation on a large scale in cost-effective growth media and the constant supply available from various industrial by-product. Gunes et al., (2019) have documented that the European brewing industry generates approximately 3.4 million tons of solid waste each year, a significant portion of which is spent yeast (Gunes et al., 2019). Alcohol, being the fifth most consumed beverage globally (Fillaudeau et al., 2006) contributes significantly to this waste. As per a study by Albanese et al. (2018), around 200 billion liters of beer are consumed worldwide annually (Albanese et al., 2018). The production of each liter of alcohol results in about 40 g of yeast as a by-product. Consequently, beer production alone discharges about 8 million tons of yeast each year (Mosai et al., 2020b). As a fungus, yeast exhibits strong resistance to metal toxicity and extreme environmental conditions at lower pH levels compared to other types of microbes due to the presence of abundant functional groups on its surface (Figure 8). Furthermore, yeast serves as an ideal model organism for studying metal-microbe interactions at the molecular level, making it a suitable biological adsorbent for metal removal.

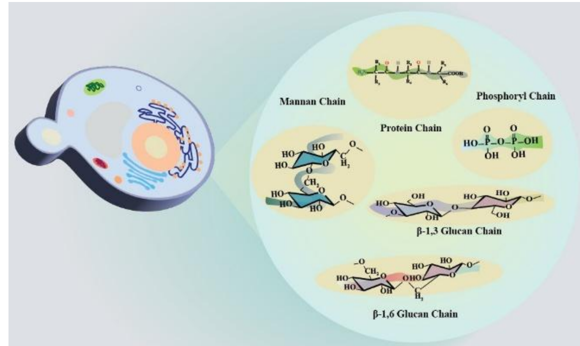

Figure 8: Structure and multiple functional groups expected to be present on the surface of yeast biomass.

Yeast is a classic and ubiquitous aquatic unicellular eukaryotic microorganism, The structure of yeast includes several key components: the cell wall, cell membrane, cytoplasm, nucleus, vacuoles, and mitochondria. A yeast cell's mass is primarily made up of about 30-50% cell wall and 10-15% protein along with other soluble elements. The cell wall itself is mainly composed of polysaccharides, accounting for about 90% of its makeup, with glucans and mannans being the predominant types. The remaining part of the cell wall consists of a small amount of protein, chitin, and lipids, which contain a variety of functional groups such as –OH (hydroxyl), –COOH (carboxyl), -–NH2 (amino), –OPO3H2 (phosphoryl), –CONH2 (amide), and –SO3H (sulfonic) (Chen et al., 2019; Mohiuddin et al., 2022). These components give the cell wall its significant natural tensile strength, similar to the epidermis of plants, which helps protect the yeast cells from external threats and prevents them from undergoing severe shrinkage. The yeast is known to have a number of amino acids such as leucine, lysine, threonine, glycine, serine, alanine, phenylalanine, valine, tyrosine and proline which makes nitrogen content approximately 10.6 wt% (Winkler et al., 2011; Nassary and Nasolwa, 2019). These characteristics made yeast a potential and sustainable biomass waste used for adsorption or removal of heavy metal removal.

Despite the advantages offered by magnetic separation techniques for the recovery of adsorbents from wastewater, several drawbacks exist. The complexity of the magnetic modification process and the increased cost associated with the application of external magnetic fields present limitations to widespread adoption (Qiu et al., 2020). These challenges underscore the need for further research to develop more cost-effective and simplified methods, thus enhancing the feasibility of utilizing biomass-derived adsorbents for wastewater remediation applications. The cell-embedded immobilization are the most general strategies to address the above-mentioned concerns. Among various immobilization carriers, aerogels display a low density, three-dimensional (3D) porous solid network with high specific surface area and readiness for modification of surface chemistry (Sun et al., 2023a). The key benefits of aerogel-based adsorbents include adjustable surface chemistry, low density, high specific surface area, and loose porous structure (Hasanpour and Hatami, 2020; Ihsanullah et al., 2022).

Aerogels as a Versatile and Efficient Remedy

Aerogels are three-dimensional solid structures that have many attractive properties such as high surface area (500–1000 m2/g), very low density (0.003–0.15 kg/m3), high porosity, nano-sized pores, low thermal conductivity, and low mean free path of diffusion, etc. (Fricke and Tillotson, 1997; Arabkhani and Asfaram, 2020). Aerogels were first synthesized by Kistler in 1931 (KISTLER, 1931). The fabrication process involves the replacement of the liquid component of a gel with a gas, such as air. This results in an ultra-porous structure that typically comprises 95-99% void spaces, making aerogels one of the lightest solid materials known today. In the present day, aerogels have found a wide range of applications, thanks to their unique properties. For instance, their high porosity and large surface area make them ideal for use in the fabrication of chemical sensors (Wang et al., 2019), filtering media (Wu et al., 2021), energy storing devices (Long et al., 2021), water repellant coatings, protective clothing (McNeil and Gupta, 2022), and environmental clean-up (James and Yadav, 2022). Aerogels can be used as a platform to support a wide range of novel materials, such as metals, semiconductors, oxides, polymers, biopolymers, microorganisms, and carbon (Ganesamoorthy et al., 2021).

Overview of aerogels and their applications in wastewater treatment

Aerogels have been emphasized in several studies as an efficient adsorbent for the removal of heavy metal and organic pollutants from wastewater. There are several parameters based on which the aerogels are classified, e.g., classification based on synthesis conditions, ingredients chemical nature, and interactive properties. The aerogel interactions with the other entities are the most important factors to decide the aerogel implications in the environment.

They are used for oil/water separation, heavy metal removal, photocatalytic reactions, removal of persistent organic pollutants (POPs), absorbance of antibiotics, removal of dyes, and halide ions, etc. (Xu et al., 2019; Sun et al., 2021; Peng et al., 2022). Comprehensive overview of aerogel applications in water treatment given in Figure 9.

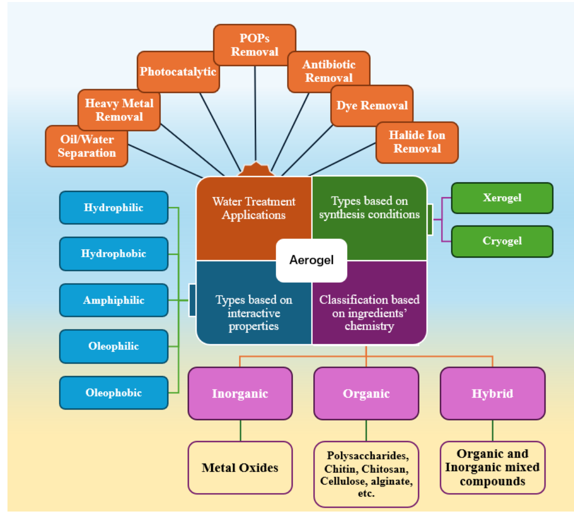

Figure 9: Classification diversity and wastewater implications of aerogels.

Advantages of using aerogels for pollutants adsorption

The use of aerogels in pollutants adsorption offers several advantages, including high surface area-to-volume ratio, tunable porosity, and ease of modification. These features enhance the adsorption capacity and selectivity of aerogels. For instance, functionalized aerogels with specific chemical groups can target and selectively adsorb heavy metal ions, improving the overall efficiency of wastewater treatment processes. They can be synthesized using organic, inorganic, or a combination of both types of precursors, as shown in Figure 9. The common schematic fabrication of aerogel represented in Figure 10. Despite the use of various inorganic or synthetic materials in aerogel formation, their performance has been unsatisfactory. For instance, graphene aerogels, despite their large surface area, have shown poor adsorption performance. Studies by Lai et al. (2021) and Huong et al. (2021) demonstrated that graphene aerogels fabricated for Cd(II) and Ni(II) removal providing adsorption capacities of only 67.34 mg/g and 108.7; 91.7 mg/g, respectively (Huong et al., 2021; Lai et al., 2021). The lack of surface chelating groups or chemical adsorption might contribute to these poor performances (Zhao et al., 2018; Jatoi et al., 2021). Therefore, choose material for aerogel framework that has large number of functional groups on their backbone such as polysaccharides.

Polysaccharides used as immobilizing carrier in the form of aerogel materials

As we shift towards a circular bioeconomy (CBE), the emphasis is on sustainable practices for resource and waste management. In this context, polysaccharides have emerged as a viable precursor for aerogels, replacing synthetic polymers (Elgarahy et al., 2023). Synthetic polymers, primarily derived from petroleum and coal, are environmentally incompatible due to their inability to integrate into natural recycling systems. They often have toxic, non-degradable precursors and their preparation cost limits aerogel applications. Conversely, polysaccharides are environmentally friendly, cost-effective biopolymers. Their abundant functional groups, such as hydroxyl (−OH), amide (−CONH2), amine (−NH2), and carboxyl (−COOH), not only contribute to make a stable aerogel structure but also helped in immobilization or embedding of other biomass like yeast, bacteria or enzymes that enhanced pollutants removal. Unlike synthetic polymers, which have poor mechanical properties, biomass polymers exhibit good mechanical strength and regenerative capabilities. Compared to traditional silica aerogels, biopolymers aerogel demonstrates high strength and can withstand up to 80% strain before pore wall collapse (Sescousse et al., 2011; Budtova, 2019). The use of polysaccharides aligns with the principles of green chemistry and sustainability, addressing environmental concerns associated with conventional wastewater treatment methods.

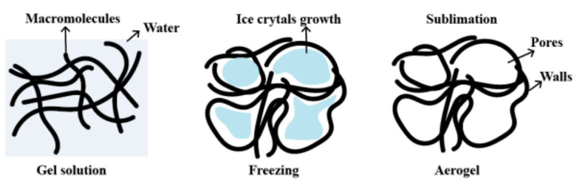

Figure 10: A systematic process for the fabrication of aerogels.

Polysaccharides, a diverse group of carbohydrate polymers linked by glycosidic bonds, can be categorized into animal, plant, and microbial polysaccharides. Chitin, a linear marine polysaccharide rich in β-(1 → 4)-linked 2-acetamido-2-deoxy-β-D-glucose, is primarily sourced from insects, crustaceans, fungi, and mollusks, with an annual global production of 6–8 million tons (Qi et al., 2021). However, its poor solubility in common solvents limits its utility. To address this limitation, chitosan, a more active form of chitin formed through deacetylation treatment, is commonly employed. Chitosan is a cationic polysaccharide characterized by hydroxyl and amino groups on its backbone (Wang and Zhuang, 2022). Among plant polysaccharides, cellulose stands out as one of the most common and abundant biopolymers with active hydroxyl groups. Chitin, chitosan, and cellulose are extensively utilized due to their abundance, availability, and biodegradability.

Scientists have harnessed these polysaccharides as aerogel frameworks for heavy metal removal in pure or modification forms. Polysaccharide-based aerogels are ultra-lightweight, highly porous three-dimensional materials derived from natural polymers such as chitosan, cellulose, or yeast polysaccharides, characterized by high surface area and strong adsorption capacity. Here are the few examples of the studies in which polysaccharides aerogels have been exploited in different ways to resolve serious challenges faced by the mankind, and an overlook of these studies provide a versatile image of the aerogel uses in wastewater treatment for the removal of heavy metals and dyes.

The study by Mo et al. (2022) addresses the global concern of water pollution by heavy metal ions and focuses on enhancing the stability and recyclability of traditional adsorbents (Mo et al., 2022). The aerogel was prepared through a two-step method involving in-situ physical/chemical double cross-linking and freeze-drying processes. The resulting aerogels demonstrated notable thermal stability, superior water stability, and excellent adsorption properties. The maximum Langmuir adsorption capacity for Cu(II) ions reached an impressive 240 mg/g. The adsorption mechanism was elucidated, involving electrostatic attraction, chelating effect, and complex formation as driving forces for the rapid and efficient adsorption of Cu(II) ions. Importantly, the aerogels exhibited outstanding recyclability, maintaining a removal efficiency of above 80% even after 10 adsorption/regeneration cycles. These findings contribute to the advancement of adsorbent technology for heavy metal removal from wastewater, aligning with the research objectives of polysaccharides-based aerogels for heavy metal removal. The incorporation of cellulose nanofibers and polyacrylamide in the composite aerogel presents promising approach for practical treatment of heavy metal ion wastewater, showcasing its potential for real-world applications.

CONCLUSION

Heavy metal contamination in wastewater remains a critical environmental challenge, necessitating the development of efficient, cost-effective, and sustainable remediation technologies. Traditional treatment methods, while effective, often suffer from limitations such as high operational costs, secondary pollution, and limited scalability. In contrast, biomass-derived materials, particularly polysaccharide-based aerogels, have emerged as promising adsorbents due to their high surface area, tunable porosity, and functional versatility.

This review highlights the potential of polysaccharide-based aerogels, especially those derived from yeast and chitosan, in addressing heavy metal pollution. These aerogels not only offer high adsorption efficiency but also align with the principles of circular bioeconomy by utilizing renewable and biodegradable resources. Their ability to be tailored for specific pollutants further enhances their applicability in wastewater treatment.

Despite their advantages, challenges remain in optimizing aerogel performance, improving mechanical stability, and enhancing reusability. Future research should focus on developing hybrid aerogels with enhanced selectivity, integrating nanotechnology for improved adsorption efficiency, and scaling up production for commercial applications. By advancing these bio-based materials, we can move toward more sustainable and environmentally friendly solutions for water purification, ensuring long-term ecological and human health protection.

DECLARATIONS

AI Usage Declaration

In line with COPE guidelines, AI-assisted tools were used only for language editing and formatting and did not contribute to scientific content, data, analysis, or conclusions. All responsibility for the manuscript rests with the authors.

Conflict of Interest Statement

There is no conflict of interest in publishing this article

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