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Is natural always greener? Evaluating the environmental performance of lab-scale biopolymer adsorbents

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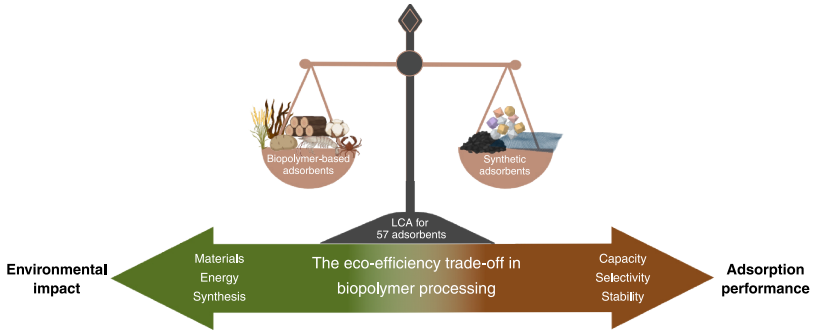
HIGHLIGHTS

- Raw biopolymer extraction often incurs high upstream environmental impacts.
- Life cycle assessments were conducted for 57 lab-based adsorbents.
- "Processing debt" from intensive chemical modification negates biopolymer greenness.
- Synthetic and commercial benchmarks exhibit superior environmental performance.
- The eco-efficiency trade-off challenges material-centric sustainability paradigms.

GRAPHICAL ABSTRACT



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ABSTRACT

Bio-based materials are widely assumed to provide sustainable alternatives to conventional synthetic technologies. However, whether this assumption holds when evaluated across production and processing pathways remains largely untested. Here, we present a systematic assessment of biopolymer-based adsorbents for water treatment by integrating synthesis analysis with partial life-cycle assessment and a performance-normalized environmental index (EPI). We analyze 49 representative biopolymer systems across six material classes and benchmark them against synthetic counterparts. The functional unit of each adsorbent was determined by their adsorption capacity alongside the number of operating cycles. Our results reveal a fundamental eco-efficiency trade-off: the environmental advantages of biopolymers are frequently offset by energy-intensive processing and the use of auxiliary chemicals, leading to environmental impacts comparable to or exceeding those of synthetic materials. Moreover, their adsorption performance does not consistently surpass conventional alternatives, resulting in limited environmental efficiency when normalized to function across multiple uses. Consequently, both lab-scale synthetic adsorbents (median EPI of 0.00535) and mature commercial benchmarks (EPI ranging from 0.00029 to 0.00084) achieved superior (lower) EPI scores compared to the median efficiencies

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of widely researched lab-scale biopolymers like cellulose and starch (0.023 and 0.0185 respectively). These findings challenge the prevailing assumption that material origin determines sustainability and demonstrate that process-level considerations could dominate environmental outcomes. We show that material-centric choice is not enough and therefore system-level evaluation is vital. We suggest that research transitioning from laboratory to industrial scale should prioritize environmental efficiency over feedstock origin, for sustainable technologies generally and water treatment applications specifically.

1. Introduction

Treating water contamination has become one of the major global challenges over the past few decades, driven by a wide range of environmental pollutants that harm human health and ecosystems (Mauter et al., 2018). Research has focused on various approaches to water decontamination (e.g., physicochemical separation and chemical oxidation) and has devoted extensive effort to developing new technologies aiming at better sustainability, selectivity, and efficiency. Biomaterials have emerged as a sustainable alternative to conventional synthetic technologies for water treatment, owing to their low cost, their assumed lower environmental impact, benign nature, and facile processing (Srivastava and Goyal, 2010; Biswal et al., 2020). In this respect, an appealing family of biomaterials commonly examined in water treatment applications such as filtration (Gough et al., 2021), adsorption (Mohanrasu et al., 2025), flocculation (Jiang et al., 2021) or as support materials (Borovik et al., 2020), are natural biopolymers, which are a group of polymeric materials produced by organisms (Yaashikaa et al., 2022). Biopolymer use is also continuously growing in other sectors, including biomedicine, the food industry, agriculture, cosmetics, and textiles (Piekarska et al., 2023) due to their ubiquitous availability, biodegradable nature, antimicrobial activity, and biocompatibility (Gough et al., 2021). Therefore, it is not surprising that biopolymers are also hypothesized to enhance or replace synthetic materials in water remediation applications. Conventional commercial adsorbents, such as ion-exchange resins and coal-based activated carbons, heavily rely on non-renewable fossil fuels. These materials can potentially leach toxic residues, have unsustainable end-of-life disposal, and their production includes greenhouse gas emissions and other harmful impacts (Mohanrasu et al., 2025).

Biopolymers can be extracted from various biological systems such as plants, microorganisms, and animals, and can be classified by their main monomeric building blocks (i.e., as amino acids, nucleic acids, and monosaccharides) into polysaccharides, polypeptides, and lipids (Khademian et al., 2020; Sohouli et al., 2022). Commonly used biopolymers in water decontamination are chitosan, cellulose, alginate, starch, and extracellular polymeric substances such as collagen, gelatin or keratin (Elgarahy et al., 2023; Mohanrasu et al., 2025). Several emerging biopolymers were recently studied in this respect, such as soy protein (Gough et al., 2021), silk (Gupta et al., 2023), and glycoproteins (e.g., mucus and mucin) (Gavriely et al., 2022; 2024). Biopolymers represent promising adsorbents for the removal of organic and inorganic pollutants from aquatic environments. They possess a high number of adsorption sites, with various types of bonds (electrostatic, hydrogen, covalent) that can accommodate different contaminants (Crini et al., 2019; Russo et al., 2021). Different pollutants such as heavy metals, organic dyes, pharmaceuticals, pesticides and some emerging pollutants (like PFOA and microplastics) have been shown to be effectively removed by biopolymers (Fierascu et al., 2023; Shija, 2025).

While natural biopolymers hold promising biocompatibility and nontoxicity features, they often lack critical mechanical properties like durability and tensile strength (Yaashikaa et al., 2022), and may have limited chemical interactions due to their natural structure (Yadav and Dutta, 2024). In addition, their stability in harsh aqueous conditions (like extreme solution pH levels, salt contents, temperatures or microbial-rich media) is usually lower than that of synthetic polymers. Fortunately, biopolymers can easily be modified to improve durability and stability through chemical modifications (such as grafting polymers, introducing of functional groups, oxidation and cross-linking), physical modifications (e.g., blending, grinding, ultrasonic treatment), composite formation (nanomaterial embedding or inorganic incorporation), and general processing (such as freeze drying, casting, thermal treatments) (Doyo et al., 2023; Mohanrasu et al., 2025). Such modifications were proven to improve their physicochemical properties (i.e., increasing surface area, charge density, mechanical strength) and ultimately result in elevated adsorption performance and stability (Khademian et al., 2020; Mohanrasu et al., 2025).

Although the use of biopolymers for water decontamination applications sounds promising, given their natural properties, they still have major drawbacks for large-scale use. First, the use of these naturally occurring resources, which are easily grown and maintained by humanity, is typically categorized as “green chemistry”, but in fact, their extraction and purification from nature may become an environmental burden (Chiew et al., 2022). Second, the use of supplemental materials, solvents, wastes, water and energy-consuming processes for the modifications that these biopolymers undergo to transform into the final product (i.e., a practical adsorbent) creates gaps in understanding the long-term environmental impacts and potential toxicity and question their sustainability (Mohanrasu et al., 2025). Third, there are economic barriers associated with biopolymer production; although they usually appear as low-cost solutions, all the extraction and fabrication processes add up to the final cost (Khademian et al., 2020). These could all affect the large-scale potential of using these biopolymers in general, and in water treatment in particular, and raise questions regarding the feasibility of their scale-up.

Life-cycle assessment (LCA) is a quantitative tool that can help estimate the environmental impacts of fabricating biopolymer-based adsorbents, considering reagents, waste, energy and components making it practical when comparing the environmental performance of two or more products (Hauschild et al., 2018). As most of the biopolymer-based products for water treatment have not yet reached large-scale production, it is hard to evaluate them in such context. Assessing emerging technologies which are still under development at low readiness level, is very challenging for the standard LCA, which traditionally is used to evaluate commercially mature technologies. When the technology has only experimental proof of concept at the lab-scale, the analysis itself include uncertainty analysis and some major assumptions (Moni et al., 2020). Therefore, prospective LCA is required to “illustrate” how such technology will operate on larger scale.

While LCAs of biopolymer-based adsorbents often report lower environmental footprints than commercial alternatives (Liu et al., 2026; Wang et al., 2026), these are typically isolated case studies conducted by the material developers, lacking standardized boundaries. More broadly, most material researchers do not conduct quantitative LCAs during the development phase at all. Instead, they rely solely on the renewable origin of the feedstock to justify a ‘green’ status, completely ignoring how extensive chemical modifications can undermine the material's overall sustainability. This reveals a disconnect between early-stage material design and environmental modeling—two fields that must be integrated at the fundamental scientific level, rather than exclusively during mature industrial scale-up. To address this critical gap, this work provides a systematic, independent partial LCA of 49 distinct biopolymer-based adsorbents, including the extraction and lab-scale synthesis of six common biopolymer classes for water

decontamination. To establish an objective baseline, we evaluate true sustainability by normalizing the environmental impact to the material's actual performance—specifically, its adsorption capacity across multiple reuse cycles. This performance-normalized framework allows us to directly compare biopolymers against lab-scale synthetic alternatives to assess whether their functional effectiveness justifies their processing footprint. Overall, by evaluating both early-stage lab synthesis and the potential for large-scale commercialization, this analysis explicitly tests whether the assumed sustainability of biological feedstocks truly translates into viable water treatment technologies.

2. Materials and methods

2.1. Search criteria and screening

The search for scientific literature was done via Scopus (by Elsevier), which serves as one of the largest databases for scientific literature. The relevant papers were collected using specific keywords: "Biopolymer", "water purification" and "pollutant", and were limited to those published between the years 2021-2025. Only research papers written in English were included and the scope was narrowed to papers about wastewater treatment. First, the main application utilizing biopolymers in the water treatment regime was identified (i.e., a search criterion with keywords for adsorption, filtration, coagulation etc. was added). The largest application was chosen for the rest of the search to maintain specificity and remain within scope. Then, the main biopolymers used in the specific application were categorized by their frequency of use. In addition, to evaluate the use of biopolymers in adsorption applications across the entire set of solutions studied, a broader literature search was conducted for the years 2000-2025 (i.e., without the specific keywords for biopolymers). The number of publications in each year was compared to the publications focused solely on biopolymers. The initial identification of relevant papers was executed using a Boolean search string applied to the Title, Abstract, and Keywords, as detailed in the SI (text S1). This primary query yielded approximately 500 articles. To ensure the reliability and quality of the life-cycle inventory data, the selection was filtered based on journals' impact, defined as journals ranking in the top 20th percentile (Q1 quartile) of their respective subject categories (e.g., Environmental Science, Chemical Engineering) according to the Scopus CiteScore and SCImago Journal Rank (SJR) metrics. Following this automated filtering, a manual full-text screening was performed to narrow the dataset to the final 49 core manuscripts. Papers were excluded if they lacked a clear mass-balance of reagents or failed to provide specific processing details and performance values, as these parameters were vital for accurate Life Cycle Inventory (LCI) construction. Finally, eight representative papers for each of the six biopolymer categories were selected: alginate (Ul et al., 2021; Wu et al., 2022; Asadi et al., 2023; Permatasari et al., 2023; D. Chen et al., 2024; Yao et al., 2024; Ahamad et al., 2025; Berk et al., 2025), cellulose (Wang et al., 2021; Ablouh et al., 2022; Mamunur et al., 2022; Rana et al., 2022; Rodrigo et al., 2022; Poornachandhra et al., 2023; Taleb et al., 2023; Demirci et al., 2024), chitosan (Zheng et al., 2020; Mirzaee et al., 2022; Majiya et al., 2023; Rahmatpour et al., 2023; El et al., 2024; R. Chen et al., 2024; Yin et al., 2024; Al-qarhami et al., 2025; Khalil et al., 2025), gum (Pandey et al., 2022; Tiwari, 2022; Zhang et al., 2024; Doufene et al., 2025; El et al., 2025; Jawhari et al., 2025; Seleka and Makhado, 2025; Tiwari et al., 2025), lignin (Jiang et al., 2023; Li et al., 2023; Sun et al., 2023; C. Wang et al., 2023; Jung et al., 2024; Bhuyan et al., 2025; Chem et al., 2025; Saaid and Ibrahim, 2025), starch (Gunawardene et al., 2021; Li et al., 2021; Mujtaba et al., 2023; Ayesha et al., 2024; Hou et al., 2024; Javad and Raayatpisheh, 2024; Wen et al., 2024; Wei et al., 2025). For full reference list and data see Supporting Information: "Inventory" Excel file.

2.2. Analysis

The main analysis consisted of four objectives: (1) Assessing the extraction of the six chosen biopolymers from their natural resource. (2) Analyzing the synthesis of biopolymer-based adsorbent in each of the 49 papers, using partial LCA method, to calculate the environmental impacts of each synthesis. (3) Detecting the performance of each adsorbent, in terms of adsorption capacity of a specific pollutant (4) Comparing the bio-based adsorbents to synthetic ones (*i.e.,* without the use of biopolymers in production), all on a lab-scale, from conducted and published research.

To assess the environmental scoring of each raw biopolymer's production from their natural resource, the openLCA program was used, with ecoinvent 3.12 APOS system database and ReCiPe 2016 Midpoint (H). This characterization method analyzes 18 environmental impact indicators, in which the H (hierarchy) is a moderate cultural perspective used as a consensus model by default (Huijbregts et al., 2017). For each biopolymer's extraction, an LCA model based on literature studies was inserted to the program (Riofrio et al., 2021; Nilsson et al., 2022; Kumar et al., 2023; Rajendran et al., 2023; Ahire et al., 2024). The input values included material and energy requirements to produce 1 kg of each raw biopolymer.

Then, to assess the environmental impact of each of the 49 biopolymer-based adsorbent synthesis, all the materials and their quantities were extracted from each synthesis, as well as their processing parameters to evaluate energy demand (see Supporting Information: "Inventory" Excel file). These values were inserted as "inputs" into the openLCA program. Each synthesis was inserted manually as a process, and a product system was created, with the following parameters: autolink process, prefer default providers and unit process. To isolate the environmental impact of material synthesis from laboratory-scale artifacts (mainly intensive-energy processing), results were analyzed at a Functional Unit (FU) of 10 g of dry adsorbent, with a secondary equipment utilization factor that allocates 10% of the total electricity demand to the specific sample, reflecting realistic capacity sharing for laboratory instruments.

Several assumptions were considered during the analysis:

1. Because explicit final product masses were rarely reported, a standardized mass balance was uniformly applied across the dataset: the final product mass was assumed to equal the total mass of the dry precursors, while all liquids (which served as solvents or washing eluents during synthesis) conservatively allocated as "wastewaters" in the output section.
2. In cases where a specific precursor was absent from the ecoinvent inventory, a "proxy" material that was selected based on structural and chemical precursor similarity was chosen, or alternatively, a mini-model process was created (Supporting Information: Table S1). For the main six biopolymers, which were not included in the database, we employed LCA model from literature papers (Riofrio et al., 2021; Nilsson et al., 2022; Kumar et al., 2023; Rajendran et al., 2023; Ahire et al., 2024).
3. Most solvents (i.e., water, organic solvents, acid and bases) were taken into consideration as inputs in the LCI for precursor dissolution or product washing. In the absence of specific quantities, a standardized ratio of 100 mL of solvent per 1 g of precursor was assumed. This value was adopted as a conservative baseline reflecting standard laboratory wet-chemistry practices (Dmitrienko et al., 2024). It is consistent with the order of magnitude observed in studies that explicitly report solvent volumes, providing sufficient liquid for complete reagent dissolution and adequate mass transfer during repeated washing protocols.

In addition, in each synthesis the processing step was also evaluated based on the energy demand in kWh, considering time, temperature, gases, vacuum etc. (Motevali et al., 2011; Stratta et al., 2020; Semenov

et al., 2025). The input for electricity was determined as low voltage (<1 kV), representing a standard for scientific laboratories. In case there were several steps in the process, their entire energy values were summed up. In cases where the specific time of the process was not mentioned in the text, it was estimated based on other similar syntheses. The energy values invested in the various processes are shown in Supporting Information: Table S2.

In the ReCiPe Endpoint method, 18 environmental impact factors are calculated by the midpoint method and then summarized into three endpoint areas: Damage to human health, damage to ecosystems, and damage to resource availability. After calculating the impact factors values with the openLCA program, all results were normalized using the World (H) 2010 normalization factors, and were summarized into one single score by the pred-defined "weight" each category is received based on its environmental importance (these steps are all intrinsically performed in the openLCA program) (Huijbregts et al., 2017).

To assess the effectiveness of each adsorbent, the adsorption capacity of the pollutant was retrieved from each paper, as it represents rigorous and comparable value for the adsorbents' performance due to standardized isotherm experiment (which in most cases are conducted at room temperature and evaluated with the Langmuir isotherm model). In case there were several pollutants, or several values for different syntheses in the same paper, the highest value was chosen. In addition, eight studies focusing on synthetic adsorbents (*i.e.,* adsorbents which are not based on one of the biopolymers) for similar pollutants, were also analyzed and assessed in openLCA in the same manner, and their adsorption capacities were extracted from each paper. These were compared to the biopolymer-based adsorbents in all parameters.

Finally, to reconcile the inherent trade-off between adsorption performance and environmental cost, we developed a multi-metric ranking tool, the performance-normalized environmental index (EPI), calculated as the environmental single scoring, divided by the adsorption capacity. The EPI was calculated for each of the 49 polymer-based adsorbents as well as the eight synthetic adsorbents.

To address uncertainties arising from lab-scale variability, a sensitivity analysis with a perturbation variation of ±50% for each input parameter was performed, in a "one-at-a-time" manner while keeping all other parameters fixed at their baseline values. The parameters considered in this study were water, raw biopolymer, electricity, and chemical solvents. The sensitivity ratio (SR) was used to evaluate the sensitivity results and was calculated as below:

$$SR = \frac{\frac{\Delta Result}{Baseline\ result}}{\frac{\Delta Parameter}{Baseline\ parameter}}$$

Where the numerator represents the relative change in the calculated environmental impact score, and the denominator represents the ±50% modification applied to the input parameter. Because total liquid waste was modeled as an aggregated effluent stream (comprising both water and solvents), the wastewater output volume was maintained at the baseline level during the solvent reduction scenario. This conservative approach ensures that the environmental benefits shown are strictly due to using fewer raw chemicals, rather than artificially lowering the impact of waste treatment.

Fig. 1 depicts a schematic flow of all the steps that were employed in our methodology towards the environmental assessment of biopolymer-based adsorbents in the water treatment field. Each step represents one part in our analysis: from the extraction of each of the six raw biopolymers, through their processing into effective adsorbents, their performance evaluation compared to synthetic adsorbents, and their scalability potential.

3. Results and discussion

Fig. 2 shows the statistical distribution of water treatment applications for biopolymers, the most used biopolymers in the past five years, and the increasing use of biopolymers in adsorption processes over the past 25 years. Among the remediation techniques, adsorption is widely used and documented for its high efficiency, intrinsic simplicity, low cost, ease of recovery, and recyclability of materials via regeneration (Russo et al., 2021; Akhtar et al., 2024). In our analysis, we focused on adsorption processes, as they accounted for the highest percentage (40%) among all other applications involving biopolymers in their synthesis (Fig. 2A).

Next, a search for the distribution of the most used biopolymers for adsorption processes was conducted and mapped (Fig. 2B). The six most used biopolymers were chosen for the rest of the analysis (Chitosan, Cellulose, Alginate, Lignin, Starch and Gum), all of which are categorized as polysaccharides (the use of the polypeptides such as collagen, gelatin or soy is less common).

In addition, to evaluate the use of biopolymers in adsorption applications across the entire set of solutions studied, a broader literature search was conducted for the years 2000-2025 (i.e., without the specific keywords for biopolymers). The number of publications in each year was compared to the publications focused solely on biopolymers. Fig. 2C shows that the use of biopolymers in water adsorption applications in literature has increased drastically over the years and reached up to 12% from the overall publications on commonly used technologies for adsorption. This indicates their growing use in lab-scale research and highlights their potential and desirability for large-scale approaches.

3.1. Environmental impact of raw biopolymer extraction

Each of the six chosen biopolymers was assessed from its initial extraction to its production into the final product using LCA methodology. All the biopolymers' extractions were modeled as processes using the openLCA program, based on other studies which performed LCA on industrial extractions for these biopolymers (Riofrio et al., 2021; Nilsson et al., 2022; Kumar et al., 2023; Rajendran et al., 2023; Ahire et al., 2024), and were compared by 18 environmental impact factors (obtained with ReCiPe 2016 Midpoint (H)). The results are shown in Table 1.

When reviewing the literature, most of the syntheses made use of a purified commercial biopolymer, which was already purified and processed to a final form (such as nanocrystals, fibers, powder, gel, etc.). Some isolated studies conducted the biopolymer extraction in-house (Poornachandhra et al., 2023; Saaid and Ibrahim, 2025). Although

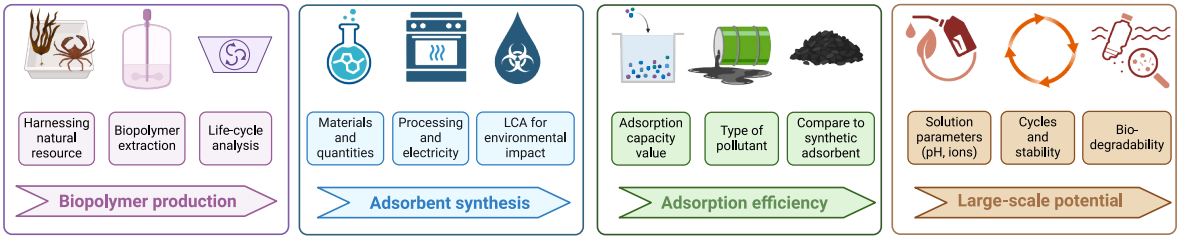

Fig. 1. Schematic illustration of methodology process to systematically analyze and classify all the syntheses that were chosen: from the basic production of the biopolymer, through the adsorbent synthesis, its adsorption efficiency, compared to benchmark, and its potential in large-scale applications.

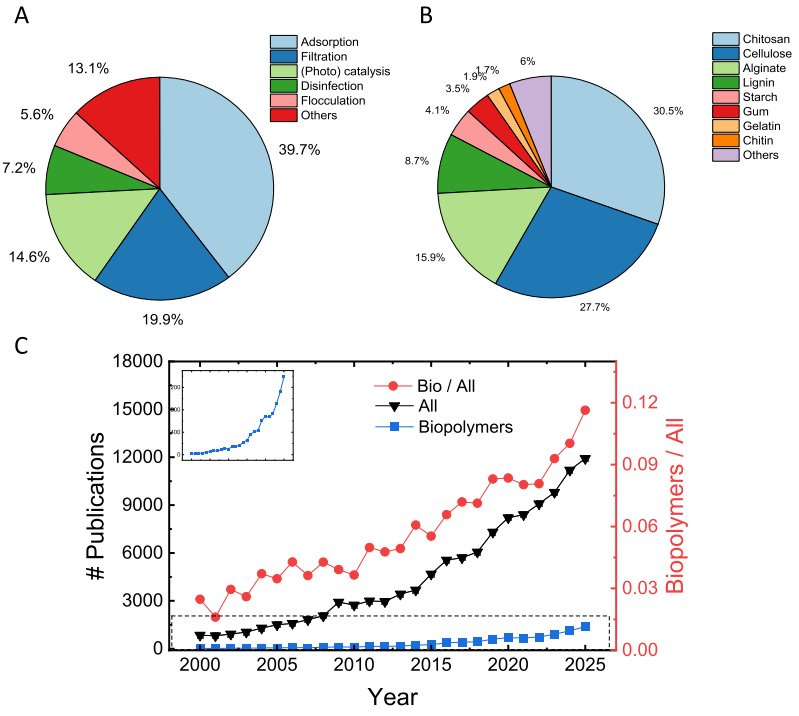

Fig. 2. (A) Pie chart illustrating the distribution of different biopolymer applications in water treatment from 2021 to 2025. (B) Pie chart detailing the relative use of individual biopolymers in adsorption research publications (2021–2025). (C) Number of publication focused on biopolymer-based adsorption for water treatment, normalized annually to the overall adsorption literature from 2000 to 2025. Literature was analyzed via Scopus database.

most biopolymers are indeed naturally occurring molecules, biodegradable and non-toxic, they cannot be found in their pure form in nature. These polysaccharides or proteins assemble into much larger natural structures which constitute a part of natural resources (plants, animals, bacteria, fungi etc.). Acknowledging and taking into consideration the required extraction process is critical in the evaluation of the biopolymers' suitability in water treatment. The production of raw and pristine biopolymers requires several extraction steps. Most of these processes include the use of alkali or acid hydrolysis, soaking, drying, filtering and other different chemical treatments (Poornachandhra et al., 2023).

To facilitate a direct comparison between the biopolymers, the environmental impacts were further aggregated to the endpoint level using the ReCiPe 2016 (H) methodology (Huijbregts et al., 2017). This allowed for the calculation of a single score that weights damage to human health, ecosystem quality, and resource availability into a single

Table 1
Heat map of midpoint impact categories for extraction of the each of the raw biopolymers, assesed with ReCiPe 2016 Midpoint (H) method. The results are expressed per 1 kg dry product of each biopolymer.

Impact categories	Unit	Chitosan	Sodium alginate	Cellulose nanocrystals	Xanthan gum	Kraft lignin	Potato starch
Fine particulate matter formation	kg PM2.5 eq	0.049	0.028	0.014	0.007	0.002	0.004
Fossil resource scarcity	kg oil eq	7.944	8.831	2.463	0.766	0.294	0.364
Freshwater ecotoxicity	kg 1,4-DCB	1.914	1.292	0.448	0.260	0.043	0.179
Freshwater eutrophication	kg P eq	0.011	0.016	0.005	0.002	0.001	0.001
Global warming	kg CO_2 eq	27.076	21.251	10.250	4.051	1.296	1.621
Human carcinogenic toxicity	kg 1,4-DCB	11.990	5.357	0.620	0.659	0.104	0.142
Human non-carcinogenic toxicity	kg 1,4-DCB	38.766	29.590	13.850	6.127	1.031	4.938
Ionizing radiation	kBq Co-60 eq	1.234	4.876	1.604	0.616	0.055	0.044
Land use	m2a crop eq	0.643	0.373	0.744	2.390	1.432	1.794
Marine ecotoxicity	kg 1,4-DCB	2.590	1.733	0.607	0.334	0.057	0.167
Marine eutrophication	kg N eq	0.004	0.001	0.001	0.005	0.002	0.004
Mineral resource scarcity	kg Cu eq	0.219	0.113	0.267	0.020	0.004	0.012
Ozone formation, Human health	kg NO_x eq	0.070	0.042	0.017	0.007	0.003	0.007
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.072	0.046	0.018	0.007	0.003	0.007
Stratospheric ozone depletion	kg CFC11 eq	0.000	0.000	0.000	0.000	0.000	0.000
Terrestrial acidification	kg SO_2 eq	0.094	0.070	0.028	0.020	0.005	0.018
Terrestrial ecotoxicity	kg 1,4-DCB	52.424	29.894	60.627	9.507	1.698	10.189
Water consumption	m3	0.238	0.135	0.220	0.100	-0.167	0.298

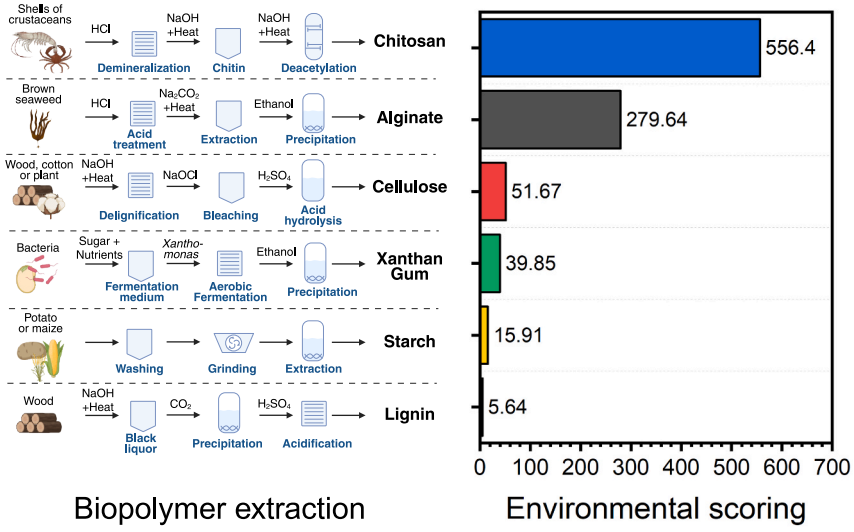

Fig. 3. Flow diagrams illustrating the extraction processes for each biopolymer, alongside their corresponding environmental single scores (per 1 kg) following normalization and weighting.

environmental point value. In addition, flow diagrams showing the main steps in the extraction processes of the biopolymers from their natural resources are shown in Fig. 3, alongside the environmental single score for each process. Other derivatives of these biopolymers that were necessary for some of the syntheses in the chosen papers were also inserted into the LCA inventory and their environmental impacts were also assessed. These received the following single scores (per 1 kg of dry product): Cellulose Acetate (46.74); Carboxymethyl cellulose (25.29); Phenolated lignin (14.51); Lignosulfonate (8.50); and tree gum (4.56).

Chitosan is frequently cited as one of the most environmentally burdensome biopolymers due to the low yield from shells (35:1 ratio) and the harsh chemical deacetylation required. In conventional chitosan production, it is prepared from chitin, which is derived from crustaceans (shrimp, crab). These shells are often available as waste from the food processing industry, making them a potential contributor to a circular economy. However, the production processes of chitosan have significant environmental impacts (Bashiri et al., 2025). During the chitin production, the demineralization stage including HCl, contributes around 23% of the total climate change impact with 6.40 kg CO_2 eq while the deproteinization process is considerably less influential at 2.58 kg CO_2 eq (Yanat et al., 2025). 1.4 kg of chitin is required for the production of 1 kg of chitosan, which is fabricated following the deacetylation process. The contribution of the deacetylation stage in a conventional process for chitosan, is the most sodium-hydroxide (NaOH)-demanding process (98%, 5.18 kg is used) and has a notable impact on the environment (Muñoz et al., 2018; Silva et al., 2024). Even when considering alternative methods to conventional ones, all processes showed significant impacts from the deacetylation, deproteinization, and demineralization steps, with notable roles played by chemicals such as NaOH and HCl (Bashiri et al., 2025).

The extraction of sodium alginate includes the seaweed production, harvesting, alginate extraction and transportation (Chiew et al., 2022). Even when considering only the dried seaweed itself as a raw material for alginate production, it has a climate impact of 6.12 kg CO_2 eq. per kg dry seaweed at post-harvest drying, and the wet form of algae right after harvest had a considerably lower climate impact of 0.16 kg CO_2 eq. per kg wet weight (Nilsson et al., 2022). A major environmental contributor is the use of high volumes of ethanol during the precipitation stage during the extraction (compared to other parameters such as heating or electricity) (Smith et al., 2024).

Cellulose is the most abundant organic polymer on earth and is the backbone of the global pulp and paper industry. Pulping is done at a multi-million-ton scale, and the environmental burden is distributed across a massive industrial infrastructure that has been optimized for energy efficiency over a century (Hao et al., 2023). Thus, cellulose extraction achieved lower score than alginate and chitosan. The final form of cellulose is usually nanocrystals or nanofibers which are prepared by sulfuric acid hydrolysis in industrial production, resulting in a large amount of alkaline and water consumption (Zhang et al., 2022). The major contribution to the environmental impact categories is from the use of NaOH, and electricity because their production and distribution are the main processes responsible for the emission of toxic substances, nutrients, greenhouse gases and acidic substances (Zhang et al., 2022). Additionally, the high mineral resource scarcity score is due to the concentrated acid hydrolysis with sulfuric acid (since sulfuric acid production is fundamentally linked to the mining of sulfur or the refining of metal ores).

Gums are divided into two types: the first includes gums produced by fermentation (such as Xanthan or Gellan gum). These polysaccharides result from the enzymatic action on a carbohydrate source, such as glucose. The second group is sourced from the seeds of trees (like karaya or guar gum) (Kumar et al., 2023). The fermentation process has higher environmental impact values due to the use of electricity and chemical media (containing inorganic salts, concentrated HCl and sugar) compared to gum extraction from trees. Overall, there are more CO_2 emissions from the production of xanthan gum than from tree gums (Kumar et al., 2023). Also, the xanthan gum had the highest value for land-use among all biopolymers, when accounting for the corn or sugar beet fields required to produce the glucose that feeds the bacteria during synthesis.

Starch can be extracted from various plants such as potatoes, wheat, cassava, or maize, but it can also be extracted from fruit wastes, especially banana peels, avocado, jackfruit, and mango seeds (Pereira da Silva et al., 2021). It was found that the largest contribution to the carbon footprint in the production stage is the agricultural process and field emissions during cultivation (Usubharatana and Phungrassami, 2015). For the growing of crops, the use of fertilizers, pesticides, and energy makes up for the largest part of the final product's impact. Agriculture is responsible for more than two-thirds of the impact for both carbon footprint and water depletion, and this industry has very

limited control over these factors and, therefore, few direct improvement possibilities. Potato starch received high values for land use and the highest score for water consumption due to crop irrigation and "wet" extraction. In addition, the starch industry typically generates little waste production. All side streams are used to produce useful products that have an economic value and waste sent to landfill or incineration is almost nonexistent (An et al., 2012).

Lastly, lignin, the second most common natural aromatic polymer after cellulose, is found in plants, where it provides stiffness to the stems (Ragauskas et al., 2014). Lignin is a by-product of wood pulping that is normally used as fuel on-site, as a major constituent of the black liquor burnt in recovery boilers, but it can also be separated and marketed. Lignin can originate from different types of pulping processes (sulfate or kraft, sulfite, soda) and from different feedstock (hardwood, softwood, straw), resulting in potentially significant differences of environmental impacts (Bernier et al., 2013).

3.2. From raw biopolymer to an active adsorbent

Following the baseline environmental analysis of raw biopolymer production, the secondary processing required to fabricate the active adsorbents was evaluated. The synthetic pathways from all 49 selected studies were modeled using openLCA, with all material modifications and energy-consuming steps categorized by biopolymer type (Fig. S1). In some syntheses, several modifications or processing steps were employed. The modifications were classified into three categories: Chemical modifications (including cross-linking, grafting, functionalization), additives (nanomaterial, nanoparticles, oxides, zeolite, metal) and polymer blending (additional synthetic or natural polymer). Chemical modification emerged as the dominant approach with 33 papers out of 49. This was closely followed by the incorporation of inorganic additives to create composites, featured in 28 of the 49 studies. Furthermore, every synthesis involved at least one physical processing step, which includes heating, drying, refluxing, vacuum oven, sonication or freeze-drying. For most of the biopolymers, medium-energy processes were employed (in the range 1-10 kWh), including oven-drying, hydrothermal processes, vacuum drying and heating during reaction. In several syntheses (12 out of 49), harsh processes were performed (above 10 kWh), mainly freeze-drying which consumes much higher rates of energy (which demands substantial electricity to maintain cooling and deep vacuum conditions over prolonged periods).

Our initial analysis revealed that electricity values were "hotspots" across all the examined papers (i.e., having a major and almost sole effect on the environmental impacts and the single scoring), since the mass of precursors synthesized at the lab-scale is negligible compared to the total energy consumed by the processes. Consequently, the relative "weight" of materials and solvents in the scoring was overshadowed by electricity usage (Fig. S2 shows a strong linearity between the environmental scoring and electricity values). However, allocating 100% of a machine's energy to a single lab-scale sample does not reflect actual conditions. Because laboratory equipment like drying ovens can accommodate multiple batches simultaneously, we applied a realistic 10% equipment utilization factor. This standard allocation accounts for lab instruments, ensuring that electricity impacts do not artificially mask the true environmental contributions of the chemical precursors and solvents.

After inserting all syntheses into the LCA program, each synthesis was evaluated by the midpoint method and received scores across 18 environmental impact categories. Two specific impact categories were selected for comparison in each synthesis to identify trade-offs between material toxicity and energy use (Fig. 4A):

- Global Warming Potential (GWP): This impact factor quantifies the integrated infrared radiative forcing increase of a greenhouse gas (GHG) and acts as a "carbon intensity" indicator. It is highly sensitive to electricity-intensive processes, such as prolonged freeze-drying or high-temperature treatments, as well as the use of solvents (e.g., Dimethylformamide (DMF), acetone or ethanol), due to their manufacturing process (Joos et al., 2013).
- Freshwater Ecotoxicity: This is a sensitive indicator for harsh chemicals, specifically measuring the biological damage caused by emitting reagents like metals, oxides, dimethyl sulfoxide (DMSO), acetone, or glutaraldehyde into water streams (Huijbregts et al., 2017).

Together, these two categories help distinguish between the potential for toxic materials to leach into the environment during the adsorbent's operation, and the impacts of harsh chemicals, solvents, and energy-intensive processes required during its production.

Most chitosan-based syntheses (blue) received the highest scores for both GWP and freshwater ecotoxicity. These papers included the use of harsh chemicals such as glutaraldehyde, cyclohexane and dioxane as well as additives like graphene oxide, magnetite and Zr-based metal-organic-framework (MOF). Furthermore, the raw chitosan precursor significantly contributes to the overall footprint. Its production carries a high intrinsic single score (5.56 per 10 g), driven primarily by the intensive use of NaOH during the deacetylation step.

Lignin (purple) and cellulose (red) based syntheses have some high ecotoxicity values, due to the use of harsh solvents (such as DMSO, ethanol, DMF, dichloromethane (DCM), dioxane) and toxic chemicals for modifications (such as glutaraldehyde, formaldehyde or epichlorohydrin). Alginate-based adsorbents (grey) received low ecotoxicity

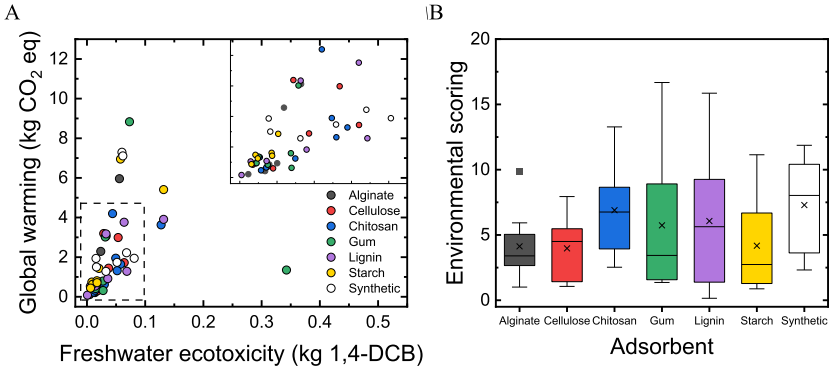

Fig. 4. (A) Global warming values vs. freshwater ecotoxicity values for each of the biopolymers-based adsorbents that were analyzed, as well as the values for the synthetic adsorbents. Inset: zoom in for the dashed-line box in the left corner. (B) Box plot of environmental single scoring distribution of each biopolymer Values are normalized per 10 g of adsorbent.

values, with almost no use of harsh solvents or hazardous chemicals. Most modifications included ionic cross-linking which is considered much greener than chemical one, but some syntheses achieved high GWP due to high-intensive processing (Wu et al., 2022; Permatasari et al., 2023). Starch-based adsorbents (yellow) got some of the highest scoring for GWP, indicating extensive processing such as long-period of freeze-drying (Wei et al., 2025), vacuum drying (Wen et al., 2024) and hydrothermal processing (Gunawardene et al., 2021); but with quite low ecotoxicity. Gum (green) had the two most extreme results, with the highest GWP in a specific paper, where a 72hr of freeze drying process was employed (Zhang et al., 2024). In another paper, the use of harsh solvents (DMF and acetone) combined with silver nanoparticles, resulted in high freshwater ecotoxicity value (Pandey et al., 2022).

To establish a comparative baseline, the 49 lab-scale biopolymer syntheses were evaluated against eight purely synthetic adsorbents (i.e., without the use of biopolymers in the process) used for similar contaminant removal (Yang et al., 2018; Liang et al., 2020; Tadjenant et al., 2020; Wang et al., 2020; Li et al., 2022; Liu et al., 2022; Huang et al., 2023; S. Wang et al., 2023). To ensure direct comparability, these synthetic pathways were modeled in openLCA using the exact methodological framework applied to the biopolymer dataset (see Supporting Information: "Inventory" Excel file). As illustrated by the white data points in Fig. 4A, natural biopolymer-based adsorbents do not inherently possess a superior eco-friendly profile compared to their synthetic counterparts. While an order-of-magnitude reduction in environmental impact might be expected for bio-based materials due to their renewable origins, several synthetic adsorbents exhibited impacts comparable to the highest-scoring biopolymers. Specifically, elevated GWP in the synthetic group was primarily driven by energy-intensive prolonged freeze-drying processes (Yang et al., 2018; Li et al., 2022), while elevated freshwater ecotoxicity resulted from the use of harsh auxiliary solvents such as ethanol and DMF (Wang et al., 2020; Liu et al., 2022).

Fig. 4B further illustrates the distribution of the aggregated environmental single scores (per 10 g of each adsorbent). While the synthetic adsorbents exhibit a slightly higher median environmental impact, the biopolymer classes (most notably chitosan, lignin, and gum) demonstrate massive variance, with several individual syntheses resulting in maximum scores that far exceed the worst-performing synthetics. To better understand these trends and evaluate the impact of inherent methodological uncertainties, a comprehensive sensitivity analysis was performed.

The sensitivity analysis assessed variations in solvent consumption, energy usage, and raw biopolymer inputs. These parameters were targeted as primary sources of uncertainty due to necessary inventory estimations: electricity inputs relied on standardized equipment allocations (e.g., assuming a 10% volume utilization for shared laboratory ovens); solvent and water quantities were frequently estimated for unquantified washing and dissolution steps; and upstream biopolymer production profiles were derived from representative literature models. Fig. 5A displays the sensitivity ratio (SR) distribution of each global parameter across all 49 studies to examine their effect on the environmental single scores. Because the results exhibited symmetrical outcomes for the ±50% variations, the presented SR values reflect the +50% scenario. Water usage demonstrated a negligible impact on the final footprint, yielding an SR below 0.03 for most assessed syntheses. Conversely, electricity and solvent consumption exerted a substantial influence, both averaging an SR > 0.3 (notably, for syntheses requiring no chemical solvents, the solvent SR naturally anchors at zero). Furthermore, a coupled scenario evaluating the combined effect of electricity and solvents yielded the highest overall SR values, confirming these parameters as dominant environmental hotspots.

Regarding the raw biopolymer input, the aggregate SR values exhibited extreme variance, ranging from near zero up to 0.94 depending heavily on the material source. To deconvolute this effect, Fig. 5B isolates the independent SR distributions for each biopolymer class. Alginate and chitosan demonstrate exceptionally high SR values, directly reflecting their chemically intensive upstream extraction processes (as previously described in Section 3.1). These findings suggest that the theoretical sustainability of natural polymers is frequently negated by the high environmental cost of extracting the raw biopolymer, along with the intense secondary processing required to achieve functional adsorption capabilities.

3.3. The environmental-adsorption performance trade-off

Relying solely on environmental footprint data does not accurately reflect whether a biopolymer is a sustainable water treatment solution. To account for this, the operational performance of each material was incorporated by extracting its specific adsorption capacity (mg g^{-1}) from the source papers. The pollutants in the examined studies were divided into four groups by their chemical classification: (1) divalent ions (Pb^{2+}, Cu^{2+}, Cd^{2+}) (2) oxyanions (Cr(VI), As(V)) (3) cationic dyes (e.g. methylene blue, Crystal Violet, Azure B, Malachite Green), and (4) anionic dyes (e.g., Methyl Orange, Congo Red, Tartrazine, Acid Red G, Indigo carmine). For the comparison, they were generally divided into metal and organic contaminants.

For each contaminant group, scatter plots were generated to compare adsorption capacity against the overall environmental single score (Fig. 6A and D), as well as the sub-impact categories for GWP (Fig. 6B and E) and freshwater ecotoxicity (Fig. 6C and F). For comparison, data for purely synthetic adsorbents (white dots) were included, separated into those removing metal contaminants (Liang et al., 2020; Tadjenant et al., 2020; Wang et al., 2020; Huang et al., 2023) and organic contaminants (Yang et al., 2018; Li et al., 2022; Liu et al., 2022; S. Wang et al., 2023). For the removal of metal pollutants, the average

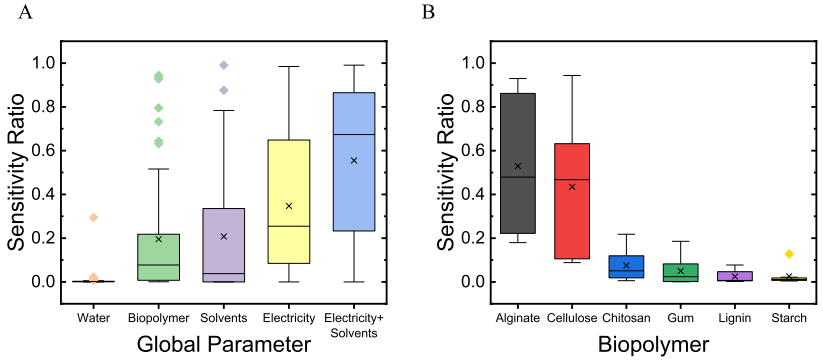

Fig. 5. Sensitivity analysis of environmental single scores. (A) Distribution of Sensitivity Ratios (SR) for global synthesis parameters (+50% variation). (B) SR distributions for the raw biopolymer inputs, categorized by biopolymer class.

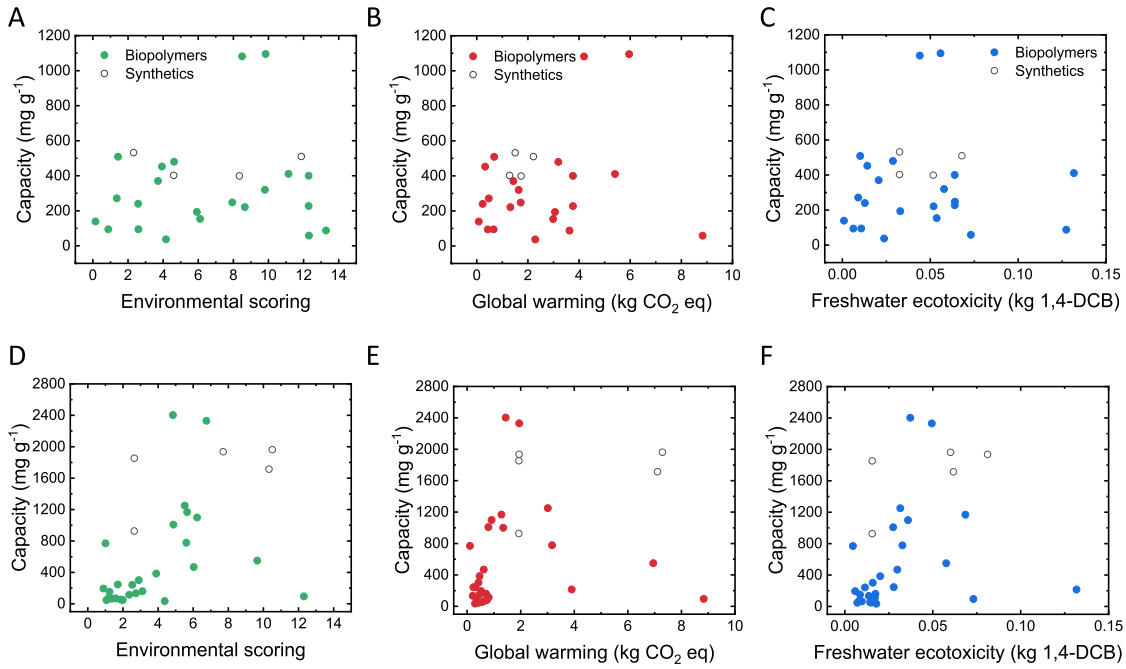

Fig. 6. Scatter plots representing each of the biopolymer-based adsorbents (colored dots) and the synthetic adsorbents, (white dots) divided by the type of pollutant. For metal pollutants:(A) Capacity vs environmental single scoring (B) Capacity vs global warming. (C) Capacity vs freshwater ecotoxicity. For organic pollutants:(D) Capacity vs environmrntal single scoring (E) Capacity vs global warming. (F) Capacity vs freshwater ecotoxicity.

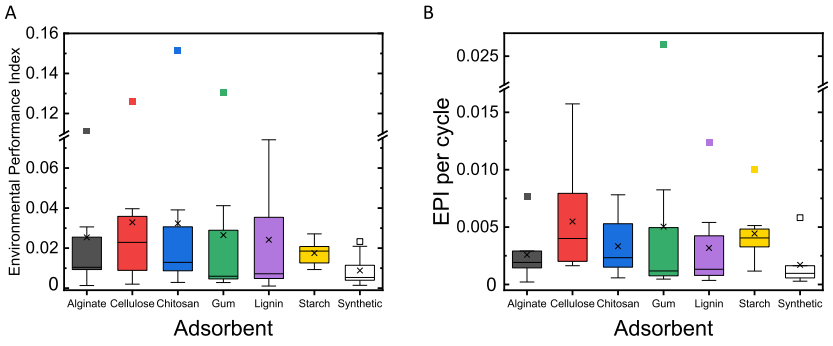

Fig. 7. Box plot of Environmental Performance Index distribution of each biopolymer-based adsorbents and the synthetic ones. (A) Without cycle-normalization. (B) with cycle-normalization.

adsorption capacity was generally higher for synthetic-based adsorbents compared to the biopolymeric ones, with the exception of two adsorbents based on chitosan(Yin et al., 2024) and alginate (Wu et al., 2022) which showed exceptional adsorption capacities towards Pb. The GWP values of the synthetic adsorbents fell in the middle of the distribution, while their freshwater ecotoxicity was slightly higher than most biopolymeric materials. In the plots for organic contaminants, it was observed that syntheses with low environmental impacts generally corresponded to very low adsorption capacities (primarily starch and alginate). While synthetic adsorbents yielded higher environmental scores than most biopolymers (including higher GWP and ecotoxicity), their adsorption capacities were also superior, with two exceptions based on chitosan (Zheng et al., 2020) and cellulose (Rodrigo et al., 2022) towards crystal violet. Overall, while biopolymer-based adsorbents may present slightly lower absolute environmental scores, their adsorption capabilities generally did not outperform the synthetic alternatives.

Taking an eco-efficiency perspective, the environmental single-scoring of each paper was normalized by the adsorption capacity, to create the EPI, to weigh the impact against the functional unit and to allow a direct comparison of environmental efficiency across diverse material classes. The lower the EPI, the better the results. Fig. 7A shows the distribution of EPI for each biopolymer-based adsorbent. The synthetic-based adsorbents got the lowest average and median values, in contrast to the trend in Fig. 4B (in which they had the highest environmental scoring), meaning that these adsorbents are not necessarily less attractive than the biopolymeric adsorbents, when considering their performance. The high median values in some of the biopolymeric-adsorbents (like cellulose- 0.02288 and starch- 0.0185) in which harsh materials, high-energy processing or excessive solvents were used, showcase that the bad performance (low capacity) was not high enough to compensate for the environmental debt (high EPI). Gum and lignin classes showed the lowest median values, suggesting they are currently the most environmentally efficient platforms in the materials that were analyzed and are comparable to synthetic ones.

To ensure that grouping different pollutant types did not change the overall trends, we also separated the EPI distributions specifically for metal cation and organic dye removal (see Supplementary Information,

Fig. S3). Notably, the synthetic category is consistently tight and very low across the board, giving it a better median and overall profile. While isolated biopolymer sub-groups (such as gum for metal adsorption) exhibited competitive median scores, the biopolymer categories showed significant environmental variance and generally higher median impacts.

To examine the full capacity of each adsorbent (both biopolymers and synthetic), the EPI of each synthesis was also evaluated across multiple uses. Most papers report that adsorbents underwent only a few adsorption-desorption cycles (with regeneration protocols in between) to see their full removal potential for the contaminants. By normalizing the EPI of each synthesis to the number of operating cycles reported in the papers (neglecting the efficiency decrease often observed after a few cycles), an interesting trend emerges (Fig. 7B). Materials that showed high environmental impacts in Fig. 4B (such as the synthetic group, lignin, and chitosan) achieved better, lower EPI per cycle scores. On the other hand, adsorbents with low initial environmental impacts (like starch and cellulose) ended up with worse, higher EPI per cycle values. This implies that heavy processing and chemical modifications can increase the initial environmental footprint, but at the same time, they create much better adsorption capacity and mechanical stability over multiple uses.

These EPI results challenge the common assumption that replacing fossil-based materials with renewable bio-based ones automatically creates a more sustainable product. Raw natural biopolymers often lack the chemical reactivity and structural porosity needed for effective cyclic contaminant removal. To achieve these properties, they must undergo extensive secondary modifications. These steps—such as harsh chemical extractions (e.g., highly concentrated NaOH for chitosan deacetylation) or energy-heavy treatments (e.g., prolonged freeze-drying)—shift the environmental impact from the raw material origin to the manufacturing phase, often canceling out the initial benefits of the biological feedstock. By contrast, while lab-scale synthetic adsorbents carry the inherent environmental burden of petrochemical extraction and refining, they are typically engineered from the bottom-up with highly tailored functional sites, porosity and chemical stability. This purpose-built design often yields superior initial adsorption capacities. When environmental impacts are normalized to this functional output across multiple cycles, the high performance of synthetic materials effectively dilutes their raw-material footprint, resulting in comparable or superior eco-efficiency.

3.4. Industrial scale-up potential and future perspectives

Despite the increase in biopolymers use in research, which is driven by growing awareness of environmental issues and their appealing advantages, the bio-based polymer market is still confronted with significant challenges compared to traditional petroleum-derived polymers (Mordor Intelligence Research and Advisory, 2025). While the use of biopolymers remains limited in the adsorption applications for water treatment, polysaccharides like chitosan are gaining ground for their cationic density and performance across a broad pH range, showing a great potential as a coagulant used in municipal wastewater treatment to coagulate and flocculate suspended particles and organic matter effectively (Fortune Business Insights, 2025). Additionally, the general market of bio-based polymers has accelerated in recent years, in other sectors such as biomedical, food-and beverage industry, cosmetics and agriculture. Therefore, our findings are relevant to other different sectors beyond the wastewater sector. Large-scale industrial applications are hampered by problems like scalability, cost, raw material availability and consistent quality of bio-based polymer synthesis, regulation, functionality and performance (Virtue market research, 2024). Understanding these market dynamics is critical when projecting how lab-scale biopolymer adsorbents might transition to industrial-scale realities.

Evaluating the scale-up potential of an adsorbent requires considering several critical parameters, such as recyclability and regeneration, operation mode (i.e., pH values, background ions, real-life water media), selectivity, and stability. Most adsorbents in the examined papers could only operate in a narrow pH range, and their performance in the presence of background ions or other pollutants was rarely evaluated. Regarding cycling, as was elaborated in section 3.3, and was shown in Fig. 7B, most papers reported that adsorbents underwent only a few adsorption-desorption cycles (mostly 5 cycles, with regeneration protocols in between), to see their full removal potential for the contaminants. Overall, expanding all these operation modes is critical for moving beyond idealized lab conditions.

Among commercial adsorbents, activated carbon (AC) is the most widely used and is highlighted as a highly effective technique for dye removal, while anion-exchange resins are standard for heavy metal remediation. A general model of commercial AC (CAC) and anion-exchange resin yielded environmental single scores of 29.14 and 24.69, respectively (per 1 kg of product), using openLCA (Table S3). These baseline single scores are highly consistent with recent mass-normalized LCAs of commercial adsorbents, which reported comparable global warming potentials for the industrial production of these materials (e.g., our modeled database GWP values of 3.28 and 4.51 kg CO_2 eq for AC and anionic resin, respectively, align with 2.15–9.52 kg CO_2 eq for AC and ~4.33 kg CO_2 eq for synthetic resins derived from previous studies) (Vilén et al., 2022; Ellis et al., 2023). Regarding functional performance, CAC from E. Merck (India) showed the ability to adsorb methylene blue (MB) up to 980.3 mg g^{-1} (Kannan and Sundaram, 2001) and 493.8 mg g^{-1} for Congo Red (Kannan and Meenakshisundaram, 2002). Similarly, Filtrasorb 400, one of the most widely used grades of AC in the wastewater treatment industry, exhibited an adsorption capacity of 476 mg g^{-1} for MB (El Qada et al., 2008). For heavy metal removal, the commercial anion-exchange resin Purolite A-400TL achieved a Pb adsorption capacity of 404.15 mg g^{-1} (Wołowicz and Hubicki, 2014), while another commercial product (IGS-300) removed Cr(VI) at a capacity of 294.11 mg g^{-1} (Leonard et al., 2023). These mature products have lower environmental impacts compared to the lab-scale biopolymer-based adsorbent, and comparable adsorption capacities (EPI ranging from 0.000297 to 0.000839 when normalized to 10 g of each adsorbent). In fact, they achieved lower scores than the upstream extraction of some raw biopolymers before the secondary adsorbent synthesis even began (e.g., 1 kg of chitosan had a single score of 556.4 and sodium alginate had 279.6 compared to 29.14 for 1 kg AC or 24.69 for anion-exchange resin), highlighting how some of these industrial extraction processes have high environmental impacts, even though they are already large scaled. In addition, some of the commercial benchmarks have exceptional performance conditions, such as the commercial anion-exchange Purolite A-400TL, which can be regenerated for at least 20 cycles (with process of backwash with NaOH 3%, then rinsing with water) and can operate in a wide range of pH (0-13) (Purolite, 2019) unlike many of the studied lab-scale adsorbents. The CAC Filtrasorb 400 is specifically designed for multiple reactivation cycles to restore its adsorptive capacity. This is performed by thermal reactivation (at 800 °C), to destroy all undesirable organics. In addition, pH has only minor effect on its adsorption performance (CalgonCarbon, 2018).

Because we are considering early stage assessment of the studied biopolymer-based adsorbents, that are only in the development phase, a genuine and fair comparison to large-scale technologies, which have already become commercially available products, cannot be achieved without proper prospective LCA (Moni et al., 2020). There are scaling factors derived from empirical scaling relationships, which can change in LCA data as technology development progresses. For instance, large industrial heaters are more efficient than a small lab oven, due to heat integration, and highly insulated continuous-flow reactors and thus can reduce thermal energy consumption per kilogram by 70-90% compared to laboratory batch processes (Piccinno et al., 2016; Ince et al., 2025); In terms of solvent usage, in a lab, 100% of the solvents are usually thrown

away, but in industrial process, 40-97% of the solvents would be recovered (mainly via distillation) (Capello et al., 2005; Constable et al., 2006); and in terms of waste, in industrial processes there are waste treatments that are included in the entire process; and the choice of materials, is optimized by their availability, cost and risk. Our sensitivity analysis (Fig. 5A) confirmed that energy and solvents consumption are the dominant parameters dictating the overall environmental footprint; consequently, applying these standard industrial heuristics yields a drastically lower quantitative projection. To quantitatively examine the potential influence of scale-up, we considered an optimistic scenario in which both electricity consumption and virgin solvent inputs were reduced by 80%. This scenario is intended as a sensitivity-based projection rather than a universal scale-up factor, allowing us to test whether substantial improvements in process efficiency would alter the comparative EPI trends. For instance, starch and cellulose, which exhibited the highest lab-scale median EPI values (0.0185 and 0.02288, respectively), would theoretically be reduced to 0.00569 and 0.00827 under industrial conditions. This reduction closes the gap between the lab-scale biopolymers and current commercial benchmarks like AC and anion exchange (EPI ranging from 0.000297 to 0.000839), although their theoretical footprint remains comparatively higher due to other parameters (e.g., other chemicals involving in the syntheses). In addition, lab-scale synthetic adsorbents would benefit symmetrically from these exact same scale-up efficiencies. Therefore, even under optimized industrial conditions, the EPI of biopolymer-based adsorbents is high. Until biopolymer processing can achieve the thermodynamic and chemical efficiencies seen in the manufacturing of commercial synthetic adsorbents, their feedstock advantage will remain masked by their processing intensity.

Beyond manufacturing constraints, an eco-efficiency trade-off is evident at the end-of-life phase. Biopolymers are consistently introduced in the literature as environmentally friendly, non-toxic, and biodegradable. Yet, after all the processing they undergo—including additives, chemical modifications, and fabrication—their actual biodegradability and toxicity levels are rarely examined or reported. In fact, only one study performed a biodegradability test (Tiwari, 2022), while another stated that the adsorbent decomposed after just one or two cycles (Khalil et al., 2025). This reveals a fundamental trade-off in adsorbent design: the mechanical stability required for cyclic water treatment inherently opposes the desired natural biodegradability of the polymer. Furthermore, the leaching of toxic cross-linkers or embedded nanomaterials during operation or disposal remains a critical blind spot. In over half of the assessed syntheses, non-organic components (e.g., graphene oxide, metal nanoparticles, or oxides) were incorporated to create composites. In these systems, it is difficult to evaluate whether the biopolymer acts as the primary active adsorbent or merely as a carrying platform for the active nanomaterial. Unlike mature industrial technologies (such as commercial activated carbon or synthetic resins), which possess established, regulated disposal protocols—including large-scale thermal reactivation, controlled incineration, and engineered landfilling to prevent environmental contamination (Baskar et al., 2022)—the disposal stage of these emerging biopolymer composites remains largely unexamined. Assessing the true end-of-life decomposition and potential toxic leaching of these complex composites is beyond the scope of this initial LCA boundary, but it must be prioritized in future system-level evaluations to accurately determine their overall cost-effectiveness compared to synthetic technologies.

However, it is important to acknowledge that the landscape of biopolymer production is rapidly evolving, with newer extraction technologies gradually lowering these initial environmental footprints. Specifically, bio-process techniques (involving enzymatic and microbial processes) can dramatically decrease the environmental impact of biopolymer extractions, offering sustainability and good product quality. For instance, bacterial cellulose as opposed to plant-derived cellulose, offers a range of features, including high levels of purity, superior mechanical and thermal attributes, long-term sustainability, high surface areas, and biodegradability (Sharma et al., 2024). Chitosan from microbial sources has recently gained attention, because of its high purity and desired properties (Ali et al., 2024). Similarly, fungal and insect-derived chitosan bypasses the extreme alkaline demineralization and deproteinization steps associated with crustacean shells (Mersmann et al., 2025). There were also attempts to optimize the traditional chitosan production with enzymatic deacetylation and reduce the reliance on harsh solvents like NaOH. It was shown GHG emissions can be reduced by 40-45% and thus lower the final LCA score (Sharma and Thangadurai, 2025). Our sensitivity analysis (Fig. 5B) strongly corroborates the potential of such upstream shifts in which chitosan yielded the highest SRs (frequently exceeding 0.70 and peaking at 0.94). Because the overall environmental score is so tightly coupled to the raw precursor, applying enzymatic extraction would cause a proportional reduction in the final life-cycle footprint. Nevertheless, these processes are not always consistent, have low yield and lack large-scale efficacy of chemical treatments (Vázquez-Aldana et al., 2025). While these emerging extraction technologies may not yet offset the intensive secondary processing required for lab-scale adsorbent fabrication, they represent a critical temporal shift toward lowering the baseline environmental footprint of the raw precursors.

Finally, several limitations of this specific study must be acknowledged. This LCA framework relies on literature-derived laboratory inventory data of variable reporting quality, requiring standardized assumptions for missing solvent volumes and synthesis details. Furthermore, the assessment is limited to a cradle-to-gate system boundary, explicitly excluding end-of-life management, toxic leaching risks, and biodegradability assessments due to a severe lack of empirical post-use data reporting. These static constraints highlight a broader limitation in current environmental modeling. Moving forward, integrating data-driven models presents a logical tool to overcome these empirical data gaps. For instance, applying a “Selection Proxy” methodology can systematically resolve missing life cycle inventory inputs by defining a descriptive characteristics space and calculating the minimum statistical distance to assign the most appropriate surrogate dataset (Meron et al., 2020). Building on these rigorous statistical frameworks, future research could apply supervised machine learning algorithms to expand life-cycle databases, mapping specific synthesis parameters directly against their resulting environmental impact scores. This approach could automatically pinpoint the critical energy and chemical thresholds where biopolymers transition from eco-friendly to high-impact materials, allowing researchers to proactively optimize greener synthetic routes.

4. Conclusion

By evaluating 49 biopolymer-based adsorbents alongside synthetic and commercial benchmarks, this study demonstrates that a natural feedstock origin does not inherently guarantee a sustainable water treatment solution. The true “green” nature of these biopolymers was not manifested in the adsorbent production; in some cases (such as chitosan and alginate), even their initial extraction from natural resources negatively influenced the environmental scoring. When evaluated through the EPI, biopolymers frequently exhibited lower overall sustainability than synthetic counterparts and commercial benchmarks like activated carbon. Therefore, the sustainability of an adsorbent is dictated by its cumulative processing intensity and functional performance, rather than the biological origin of its raw materials.

A critical look at recent development trends explains this discrepancy. Over the past few years, the requirement to achieve maximal functional performance (e.g., higher adsorption capacities) has frequently led to increasingly complex functionalization, harsher cross-linking steps, and energy-intensive drying methods. Consequently, newer biopolymer synthesis technologies do not inherently lower environmental footprints; instead, they acquire a “processing debt” that often inflates lab-scale energy and solvent demands. This constitutes a

fundamental compromise: adding more modifications improves performance and reusability, but it lowers the overall sustainability of manufacturing the material. Ultimately, this eco-efficiency trade-off challenges the widespread material-centric paradigm in sustainable design and highlights the critical need for performance-normalized environmental metrics.

CRediT authorship contribution statement

Shira Gavriely: Writing – original draft, Methodology, Investigation, Conceptualization. **Vered Blass:** Writing – review & editing, Validation, Software, Methodology. **Shachar Richter:** Writing – review & editing, Resources. **Ines Zucker:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.149443.

Data availability

Data will be made available on request.

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