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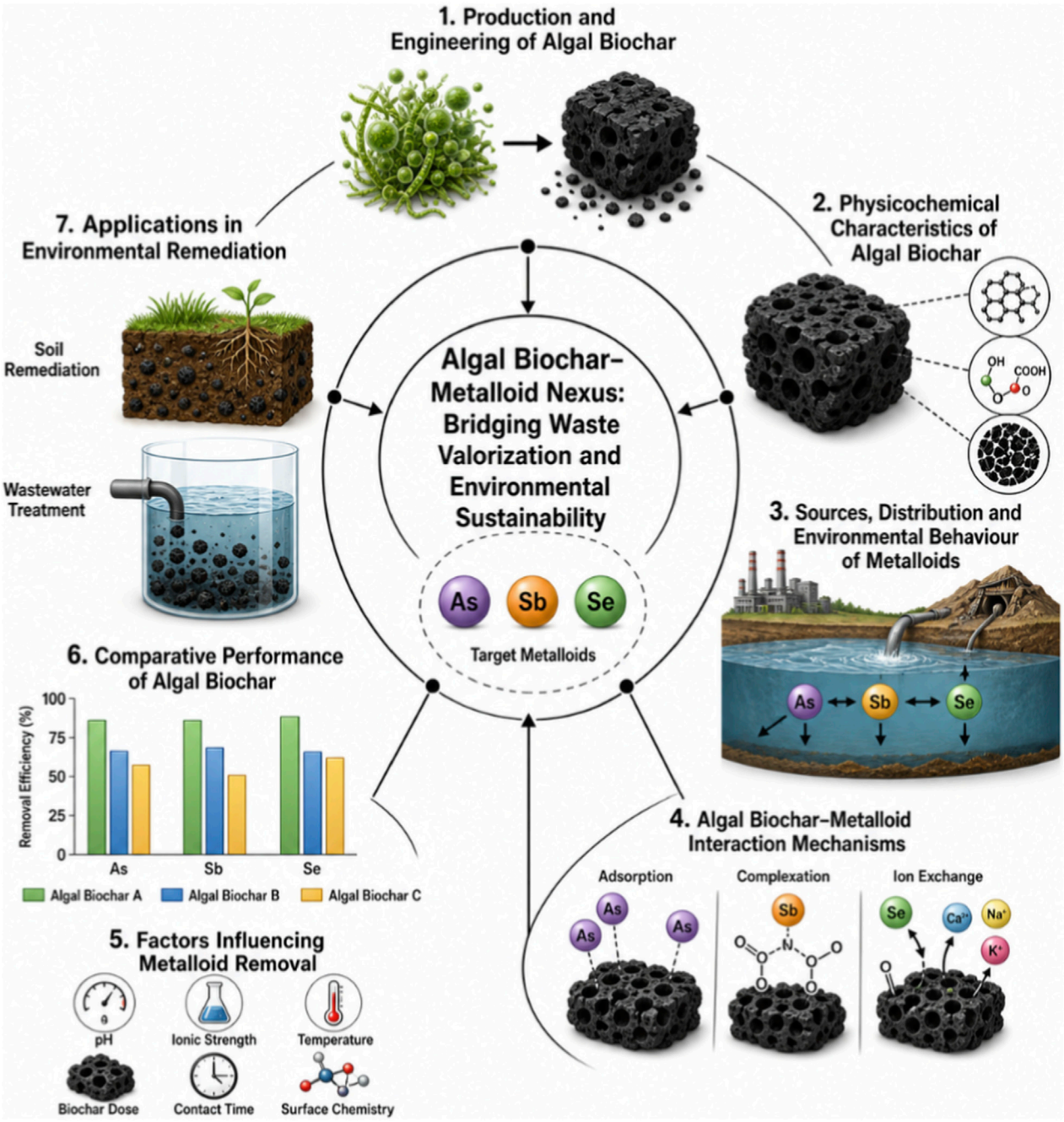
Algal biochar for metalloid removal: from waste algae to cleaner water

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Arsenic (As), antimony (Sb), selenium (Se), and tellurium (Te) are released widely by mining, smelting, fuel combustion, and agrochemical use. These metalloids persist, bioaccumulate, and remain toxic at trace concentrations. Affordable and sustainable remediation options are therefore needed. Algal biochar, produced from microalgal and macroalgal biomass through thermochemical conversion, has emerged as a candidate adsorbent. Its appeal rests on a mineral-rich ash fraction, abundant surface functional groups, low feedstock cost, and compatibility with circular-bioeconomy principles. This review provides a comprehensive synthesis of recent advances in algal biochar production, physicochemical characteristics, surface modification strategies, and mechanisms governing metalloid removal. Literature published between 2006 and mid-2026 was identified, screened, and selected using the PRISMA 2020 reporting framework, and the evidence was synthesised narratively; no meta-analysis was performed. The synthesis examines how feedstock type, production conditions, and solution chemistry influence adsorption performance. The review discusses key removal mechanisms, including electrostatic attraction, surface complexation, ion exchange, precipitation, redox transformation, and pore filling, and compares algal biochar with conventional biochar, activated carbon, and nanomaterial-based adsorbents. Applications in wastewater, groundwater, soil, constructed wetlands, and industrial effluents are assessed alongside waste-biomass valorisation and life-cycle sustainability. The evidence is strongest for As, moderate for Se, and sparse for Sb and Te. Most reported data come from single-metalloid batch experiments in synthetic solution, whereas field-scale performance, real-matrix competition, regeneration, and the fate of spent, metalloid-laden biochar remain poorly documented. These gaps, rather than adsorption capacity alone, currently limit practical deployment.

KEYWORDS
adsorption, algae, biochar, circular bioeconomy, metalloids, remediation, sustainability, waste valorisation



GRAPHICAL ABSTRACT

1 Introduction

Metalloids, principally arsenic (As), antimony (Sb), selenium (Se), and tellurium (Te), together with emerging elements such as germanium, bismuth, and polonium, constitute a growing class of global pollutants with severe implications for ecosystems and human health (Davamani et al., 2026). Occupying the diagonal boundary between metals and non-metals in the periodic table, these elements display distinctive thermodynamic and kinetic behaviour: redox-active species such as As and Se interconvert among multiple oxidation states and undergo biogeochemical transformation, whereas others remain comparatively inert (Arumugam and Becker, 2014). Their environmental burden is driven largely by anthropogenic activity—mining, ore smelting, fossil-fuel combustion, waste incineration, and the application of agrochemicals—superimposed upon natural weathering. Even at trace concentrations, metalloids impair metabolic processes, bioaccumulate and biomagnify through food webs, and are associated with carcinogenic, teratogenic, developmental, and reproductive disorders in non-target organisms (Barik et al., 2025). The rising industrial demand for Sb, Se, and Te in particular signals an intensifying threat, and regulatory limits set by the World Health Organization, the United States Environmental

Protection Agency, and the European Union (for example, a drinking-water ceiling of 10 μg L^{-1} for total As) underscore the urgency of effective, affordable remediation (Peasah et al., 2024).

The four metalloids of greatest concern differ markedly in their environmental chemistry, which shapes both their risk profiles and the strategies needed to remove them. The most prevalent and toxic is As, occurring chiefly as arsenite (As(III)) under anoxic conditions and as arsenate (As(V)) under oxic conditions; it is mobilised by mining, smelting, and fertiliser use and by the reductive dissolution of Fe and Mn oxides; chronic exposure is carcinogenic and teratogenic (Mudhoo et al., 2011). Sb, predominantly Sb(III) in the environment, is released by mining, metallurgy, coal combustion, and waste incineration, with photoreduction, precipitation, and adsorption acting as the main attenuation pathways (Li et al., 2018). Se is unusual in being biologically essential yet toxic above a narrow window, cycling between selenide, selenite, and selenate forms, whose mobility and plant uptake are strongly pH dependent. Te, by contrast, is a rare and poorly monitored element with a speciation and aquatic behaviour that remains largely unresolved, even as industrial demand rises steeply. This diversity in oxidation state, charge, and mobility means that a single sorbent must contend with anionic, neutral, and cationic species simultaneously, and explains why removal performance differs so widely among the metalloids (Fernández-Martínez and Charlet, 2009).

In parallel, algal biomass has emerged as a versatile and renewable bioresource. Micro- and macroalgae are cultivated or are harvested from natural blooms and wastewater systems to yield biofuels, food supplements, fine chemicals, fertilisers, and animal feed. They combine rapid growth and high productivity with the ability to grow in fresh, marine, or nutrient-rich (eutrophic) waters, and microalgae can be propagated on wastewater streams, coupling biomass generation with nutrient recovery (Singhal et al., 2021). However, large-scale cultivation, residues from algae–biodiesel processing, biosorbent residuals, and the recurrent nuisance of harmful algal blooms generate substantial quantities of surplus and waste algal biomass, the disposal of which is costly and environmentally problematic. Valorising this residual biomass is therefore both an economic and an ecological imperative and aligns directly with circular-bioeconomy objectives that seek to return nutrients to soils while minimising waste (Sarwer et al., 2022).

Pyrolysis and related thermochemical routes convert algal biomass into three principal products: biochar, bio-oil, and gas. Of these, biochar (ABC) has attracted particular interest as a low-cost, carbon-rich material for the remediation of soil and water (Khan et al., 2026). Compared with conventional lignocellulosic feedstocks, algal biomass has a higher inorganic (ash and mineral) content, lower C–N and C–P ratios, lower lignin content, and a homogeneously distributed mineral fraction; these features can favour the formation of metal-oxide-bearing chars with appreciable affinity for anionic and cationic metalloid species (Nguyen et al., 2023). Inherent or engineered metal (oxy)hydroxides, especially iron-based phases together with surface functional groups (carboxyl, hydroxyl, carbonyl, and phenolic), and basic ash constituents endow algal biochar with multiple potential binding pathways, including electrostatic attraction, surface complexation, ion exchange, precipitation/co-precipitation, redox transformation, and hydrogen bonding (Masud et al., 2025). Surface modification, activation and the synthesis of composite or nanostructured biochars can further enhance porosity, surface charge, and metalloid uptake. Integrating algal-waste valorisation with metalloid remediation thus offers a route to simultaneous pollution control, resource recovery, and carbon sequestration (Thamarai et al., 2024).

Despite this promise, the evidence base remains fragmented. Algal biochar has been studied far less than plant-derived biochar, and its physicochemical characterisation in the specific context of metalloid removal surface area, pore structure, point-of-zero charge, mineral composition, and functional-group chemistry has not been systematically consolidated (Sadia et al., 2026). Removal efficiencies and the factors that govern them (pyrolysis temperature, solution pH, initial concentration, competing ions, contact time, temperature, and natural organic matter) vary widely and are sometimes contradictory across studies (Nasrollahpour et al., 2025). Critical questions remain open: can algal biochar fundamentally alter the speciation, mobility, and bioavailability of metalloids, as has been demonstrated for several metals? Are its capacities for Sb, Se, and Te comparable to those achieved with conventional sorbents? Is metalloid uptake governed chiefly by surface affinity, by complexation at specific functional groups, or by mineral-mediated precipitation? Are waste-derived algal biochars genuinely competitive when judged not only on remediation performance but also on raw-material economy and life-cycle sustainability? A coherent synthesis that links algal biochar production, characterisation, interaction mechanisms, and removal performance with waste valorisation and ecological risk is currently lacking (Anosike-Francis et al., 2026).

This review addresses that gap by providing an integrative assessment of the algal-biochar metalloid nexus. Micro- and macroalgal biomass cultivated or recovered from wastewater and blooms can be converted by pyrolysis, hydrothermal carbonisation, microwave-assisted carbonisation, gasification, or torrefaction into biochars and activated carbons that actively participate in the removal of As, Sb, Se, and Te from water and soil (Fernández et al., 2025). Modifying production conditions or fabricating hybrids, nanocomposites, and composite structures can markedly enhance removal efficiency, yet the relationship between sorption capacity and biochar's physicochemical properties remains imperfectly resolved (Murtaza et al., 2022). Accordingly, this review synthesises current progress on (i) the physicochemical characteristics and metalloid-interaction mechanisms of algal biochar; (ii) the factors influencing metalloid removal; (iii) comparative removal performance against plant-derived biochar, activated carbon, and nanomaterials; (iv) applications in wastewater, groundwater, soil, constructed-wetland, and industrial-effluent remediation; (v) the integration of algal biochar into waste-valorisation and circular-bioeconomy strategies; (vi) life-cycle sustainability and associated environmental and ecological risks (Qin and Chen, 2025).

To ensure transparency and rigour, the review follows the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA 2020) guidelines, comprising a structured search, screening, and selection protocol detailed in our methodology. By bridging waste valorisation and environmental sustainability, the algal-biochar–metalloid nexus is positioned not merely as a remediation technology but as a component of a broader strategy for resource recovery, pollution abatement, and a circular bioeconomy (Fernández et al., 2025).

2 Methodology

The review process follows PRISMA 2020 guidelines, ensuring a comprehensive examination of the current state of knowledge on

algal biochar and its potential interactions with metalloids. A literature search was conducted in three electronic databases—Scopus, Web of Science Core Collection, and Google Scholar (Phiri et al., 2024)—which together cover journal articles, book chapters, and conference papers published between 2006 and mid-2026. The same date window and the same three databases apply throughout Sections 2.2–2.5. The Scopus database was searched with the string ("algae OR algal OR algae-derived OR algae-based OR algal-derived OR algal-based") AND ("biochar" OR "biochars" OR "biocarbon" OR "biocarbons") AND ("metalloid" OR "arsenic" OR "antimony" OR "selenium" OR "tellurium" OR "germanium" OR "bismuth" OR "polonium") in the metadata fields; a complementary search for articles citing the quantitative synthesis studies utilising the individual interaction mechanisms and the factors influencing sorption efficiency was performed in Google Scholar.

Selection criteria began with English-language manuscripts published in peer-reviewed journals, books, or conference proceedings that specifically discussed the application of algal biochar in the removal of metalloids from water or soil systems (Lima et al., 2025). At least one element of the metalloid group arsenic (As), antimony (Sb), selenium (Se), tellurium (Te), germanium, bismuth, or polonium had to be targeted. Metalloids were defined as semimetals located along or adjacent to the dividing line of metals and nonmetals in the periodic table and including at least As, Sb, and Se (Babula et al., 2009). Screening followed a three-step approach: title screening, abstract screening, and full-text assessment. Two reviewers screened all records independently; percentage agreement was 91.9% and Cohen's κ was 0.95, with all disagreements resolved by discussion (reported once here and in Section 2.5). A data-extraction form captured the target species, study context, and keywords associated with the interaction mechanisms and factors affecting performance. Quality was assessed using a modified version of the 15-point checklist for studies assessing the application of biochar (Breton et al., 2013). PRISMA 2020 was used here as a reporting and transparency framework for identification, screening, and selection only. No meta-analysis was undertaken, and the synthesis presented in Sections 3–12 is narrative and descriptive.

2.1 Review protocol and reporting guidelines (PRISMA 2020)

The review followed PRISMA 2020 guidelines to enhance its accuracy and completeness. The PRISMA Statement, consisting of a 27-item checklist and five-phase flow diagram, was developed to help authors prepare systematic reviews and meta-analyses and to assist journal editors and reviewers by providing the necessary information for assessment. Accurately adhering to these evidence-based, clear, and complete reporting recommendations increases the accuracy and usefulness of systematic reviews, thus improving the reliability of evidence-based decisions (Woodruff and Sutton, 2014).

PRISMA 2020 and the new research synthesis framework that it incorporates, including the new Template for Intervention Description and Replication (TIDieR) guide, are now the foundation for the PRISMA Extension for Scoping Reviews and the other extensions dealing with diagnostic test accuracy, network meta-analysis, and individual patient data analyses. Future additions will address the need for an evidence-based process for risk-of-bias assessment and for the preparation of scoping reviews (Sarri et al., 2022). Because the included studies differ widely in feedstock, sorbent form, target metalloid, water matrix and experimental design, no common effect size could be defined. Accordingly, no pooled estimate, study weighting or heterogeneity statistic was calculated, and the term "meta-analysis" is not applied to any part of this review. Quantitative results are reported as observed ranges drawn from individual studies.

2.2 Literature search strategy

The literature search followed the PRISMA 2020 framework and aimed at capturing research findings published in peer-reviewed journals, meeting the required criteria for extraction and synthesis. The search words "Algal Biochar or Algae-Derived Biochar" and "Metalloid or Metalloids" were used in combination in Google Scholar (basic and advanced search). Publisher platforms such as ScienceDirect, Wiley Online Library, and SpringerLink were used only to retrieve full texts of records already identified in Scopus, Web of Science, or Google Scholar and were not treated as independent search databases (Fernández et al., 2025). Additional keyword strings included "Biochar from Algae"; "Biochar–Contaminant"; "Algae Biochar and Waste Treatment"; "Algal Biochar–Environmental Remediation"; "Algal Biochar–Wastewater Treatment"; "Algal Biochar–Groundwater"; "Algal Biochar–Soil Amendments"; "Algal Biochar–Metalloid Adsorption"; "Algal Biochar–Selenium and Soil Quality"; "Algal Biochar in 'Constructed Wetlands'"; "Algal Biochar in Industrial Effluents"; "Algal Biochar–Resource Recovery"; "Algal Biochar and C–C Economy"; "Algal Biochar and Risk Assessment". The term "Wastewater Treatment" was combined with different classes of "Algal Waste Biomass", and the terms "Groundwater" and "Soil" were employed in combination with major types of "Algal Waste" (Al-Jabri et al., 2020).

Research published between 2006 and mid-2026 met the inclusion criteria when focused on algal biochar or biochar produced from algal feedstocks subjected to pyrolysis/thermal processing in algal biomass at any scale. Data synthesis was extensive, covering (but not limited to) general aspects of algal biomass pyrolysis/pyrolytic biochar.

2.3 Databases and search keywords

The literature search was performed in the Scopus and Web of Science Core Collection databases using the Boolean operator "AND" and combinations of the following keywords: "algal," "biochar," "metalloid," "arsenic," "antimony," "selenium," "tellurium," "precursors," "removal," and "adsorption." The search covered publications from 2006 up to mid-2026, consistent with Sections 2, 2.2. The resulting dataset assembled through these sources formed the basis for a structured qualitative synthesis of current knowledge relating to algal biochar. Progress made to date, prevailing knowledge gaps, and future knowledge needs are also highlighted.

Search terms and their corresponding synonyms used in the first search included "(algal OR "algal biochar") AND metalloid AND (arsenic OR antimony OR selenium OR tellurium) AND ('removal' OR 'adsorption')". The following metalloids were introduced subsequently: Arsenic (As): (arsenic OR As); Antimony (Sb): (antimony OR Sb); Selenium (Se): (selenium OR Se); Tellurium

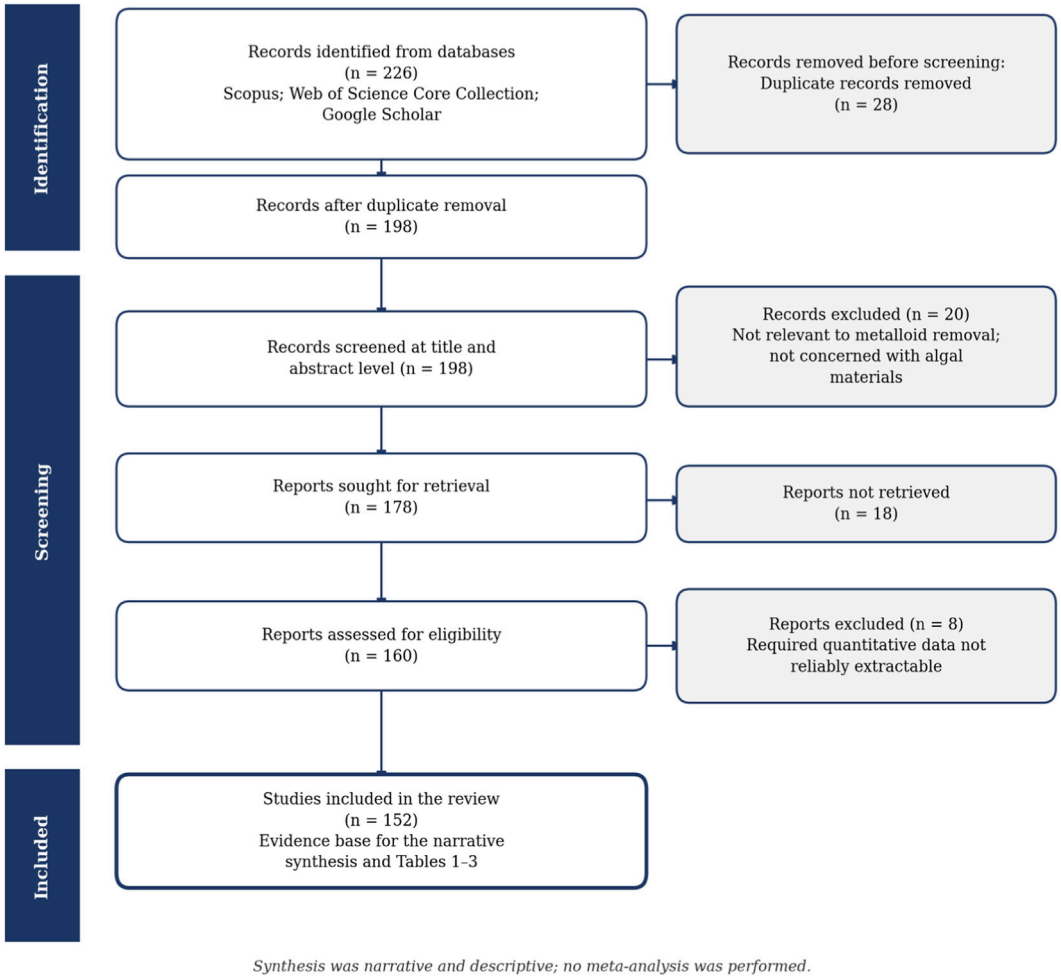


FIGURE 1
PRISMA 2020 flow diagram for the identification, screening, and selection of studies. Records were identified in Scopus, the Web of Science Core Collection, and Google Scholar, deduplicated, screened at title and abstract level, and assessed in full text against the inclusion criteria in Section 2.4. The 152 included studies form the evidence base for the narrative synthesis; no meta-analysis was performed.

(Te): (tellurium OR Te). Meta-analyses, reviews, and perspective commentaries were actively excluded from the search results.

2.4 Inclusion and exclusion criteria

All records were considered for inclusion if they described any aspect of the biochar sourced from algae or algal-derived biomass and its interaction with the metalloids in a techno-economic, environmental, ecological, or regulatory context. Publications without primary results (e.g., reviews, editorials, patents and letters) and those reporting on plant- and animal-derived biochar were excluded. The rationale for excluding plant-derived biochar was that the different nature of the feedstock has a significant effect on the characteristics and performance of biochar, the aquatic phase of the biogeochemical cycle, and its fate and transport in the environment. Similarly, the exclusive use of animal-derived biochar for wastewater treatment is either economically or environmentally unsustainable. Studies characterising the metalloids in the context of traffic emissions and atmospheric precipitation were excluded from consideration. Finally, literature examining (1) mechanisms of antifouling and adsorption of metalloids, (2) interactions of algae with metalloids through permeation, and (3) from living organisms other than humans was not retained. Inter-reviewer reliability is reported once, in Section 2.5, and applies to all screening stages. Disagreements were resolved through consultation and consensus.

2.5 Study screening and selection process

A multi-step process screened study titles and abstracts, followed by full-text scrutiny of the remaining articles, in accordance with the PRISMA 2020 flow (Figure 1). A binary decision tree clarified selection reasoning, yielding excellent agreement between the two independent reviewers (percentage agreement 91.9%; Cohen's $\kappa = 0.95$). In the identification stage, 226 records were retrieved from the three databases. After removing 28 duplicate records, 198 unique records remained for screening. These were first screened at the title and abstract level, restricting the corpus to English-language publications and assessing topical relevance, novelty, geographical scope, and the promotion of circular-bioeconomy principles; 20 records were

TABLE 1 Comparison of microalgae and macroalgae as feedstocks for algal biochar production (Li et al., 2025; Poo et al., 2018; Borowitzka (2016); Awasthi et al. (2026).

Attribute	Microalgae	Macroalgae
Organism type	Unicellular	Multicellular (thallus)
Cell/thallus size	2–200 μm	cm to several m
Growth cycle/doubling time	Hours to days	Weeks to months
Areal productivity	High (≈15–30 gm^{-2} d^{-1})	Moderate
Cultivation medium	Fresh, marine, or waste water	Mainly marine/coastal
Harvesting	Energy-intensive (centrifugation)	Manual/mechanical, easier
Protein (% dry wt)	7–55 (up to ≈60)	5–25
Lipid (% dry wt)	15–55 (some >70)	1–5
Carbohydrate (% dry wt)	20–40	25–60 (alginate, fucoidan)
Lignin (% dry wt)	Negligible	Low (<10)
Moisture, fresh (%)	80–90	70–90
Ash/mineral (% dry wt)	4–25	10–35
Carbon (% dry wt)	45–55	25–45
Nitrogen (% dry wt)	4–10	1–4
C:N ratio	5–10	8–20
Dominant ash minerals	K, P, Mg, Fe	Ca, K, Na, Mg, Fe, S
Volatile matter (% dry wt)	60–80	55–75
Biochar yield, slow pyrolysis (%)	25–48	20–42
Typical char BET (m^2 g^{-1})	<5 to ≈50 (≤1,200 if activated)	<5 to ≈120

excluded at this stage because they were not relevant to metalloid removal or did not concern algal materials, leaving 178 reports sought for full-text retrieval. Of these, 18 could not be retrieved, and the remaining 160 reports were assessed for eligibility. A further eight were excluded because the required quantitative data could not be reliably extracted. This yielded a final set of 152 studies, which were analysed using a binary decision framework to identify the factors and conditions influencing algal biochar's ability to remediate metalloid pollution and which constitute the evidence base used to build the entire manuscript. Further decisions focused the review by filtering for metalloids, major forms, fates and sources. These 152 studies form the evidence base for the narrative synthesis and for Tables 1–3; they were not pooled statistically.

2.6 Data extraction and quality assessment

Carefully selected forms organised data extraction and quality assessment, facilitating a structured synthesis of both qualitative and quantitative information. The Excel-based data extraction form included an identifier for direct retrieval of source publications. Variables captured across all studies included (1) first author, publication year, and title; (2) keywords and country of first author or corresponding author; (3) publication title, journal, and type (original research, review, conference paper); (4) source of biochar; (5) metalloid(s) addressed; (6) dominant influencing factors; (7) individual/combined treatment performance; (8) salient engineering approaches; (9) application domain; (10) waste valorisation aspect; and (11) quality assessment scoring for originality, methodology, results, and interpretation. Separate forms for qualitative and quantitative synthesis included all variables above, plus details of the uptake mechanisms underpinning environmental engineering and resource renovation application. Quality assessment adhered to a simple criteria-based approach, with scores out of five allocated for the originality, methodology, results, and interpretation sections of each original research paper or conference proceeding. Quality scores were assigned independently by two reviewers and discrepancies resolved by consensus; agreement statistics for study selection are reported in Section 2.5.

Primary articles formed the basis of both qualitative and quantitative syntheses. The qualitative exploratory assessment examined mechanisms of interaction between algal biochar and metalloids, the factors influencing removal, and the sources of performance data. Environmental remediation applications were provisionally categorised into wastewater treatment, groundwater remediation, soil remediation, constructed wetland integration, and industrial effluent treatment (Kumar et al., 2025). The quantitative component was descriptive rather than statistical. Reported maximum adsorption capacities (qmax) and removal efficiencies were tabulated together with the experimental conditions under which they were obtained, converted to common units where the source permitted, and compared as ranges across metalloids, feedstocks, and comparator sorbents—plant-derived biochars, activated carbons, and nanomaterials. No effect sizes were computed, no study weighting was applied, and no heterogeneity statistics were derived. This synthesis therefore does not constitute a meta-analysis, and the ranges reported in Sections 8, 9 should be read as the spread of published values rather than as pooled estimates (Qasim et al., 2026).

3 Algal biomass as feedstock for biochar production

Linking algal biomass to the production of biochar supports the valorisation of aquatic microalgae and marine macroalgae, which have seen increased rates of growth because of eutrophication, red tide, algal bloom, and climatic change. While metallic biochar originating from land plant sources has been extensively studied, progress in algal biochar is relatively limited (Abideen et al., 2022). However, algae can be cultivated in salt water, freshwater, or in eutrophic waters laden with nutrients. Several sources of biochar derived from algae exist, including cultured algal biomass, algal biomass originating from wastewater, and residual algal biomass after biodiesel production. Additionally, macroalgal species, such as red or brown macroalgae, exhibit higher hydrogen and nitrogen concentrations than terrestrial biomass, making them richer in nutriments and/or biofertilisers (Nautiyal et al., 2016). The

TABLE 2 Representative production (pyrolysis) conditions and physicochemical properties of algal biochars.

Feedstock	Process	Temp (°C)	BET (m^2 g^{-1})	Pore vol. (cm^3 g^{-1})	Yield (%)	References
Chlorella sp	Slow pyrolysis	500	8–35	0.02–0.08	35–48	Law et al., 2022
Chlorella pyrenoidosa ($NaHCO_3$-mod.)	Fast pyrolysis	750	≈1282	0.40–0.60	20–30	Rohman et al., 2024
Chlorella vulgaris	Pyrolysis	450–550	5–25	0.01–0.05	30–45	Law et al., 2022
Spirulina (*A. platensis*)	Slow pyrolysis	550	5–20	0.01–0.05	30–45	Binda et al., 2020
Scenedesmus obliquus (chitosan-mod.)	HTC/pyrolysis	300–500	25–90	0.05–0.12	30–50	Law et al., 2022
Nannochloropsis sp. (K_2CO_3, MW)	Microwave-assisted	600–700	400–900	0.30–0.50	22–35	Kusmayadi et al., 2025
Desmodesmus sp. (K_2FeO_4, magnetic)	Pyrolysis	200–600	20–120	0.05–0.20	30–50	Tian et al., 2025
Spirogyra sp.	Slow pyrolysis	450–600	<10	<0.03	28–42	Binda et al., 2020
Saccharina japonica (kelp)	Pyrolysis	400–700	<5 (low)	<0.02	>40 (low T)	Poo et al. (2018)
Sargassum fusiforme	Pyrolysis	500–700	<10	<0.03	30–45	Poo et al. (2018)
Sargassum sp	Slow pyrolysis	400–600	5–40	0.02–0.08	30–45	Farobie et al., 2022
Ulva sp. (green macroalga)	Pyrolysis	500–700	5–30	0.02–0.07	25–40	Poo et al., 2018
Laminaria sp	Pyrolysis	500–600	5–25	0.02–0.06	28–42	Poo et al., 2018
KOH-activated algal char	Pyrolysis + KOH	600–800	600–1500	0.30–0.70	15–30	Law et al., 2022
Algal hydrochar	Hydrothermal carbonisation	180–250	<10	<0.03	45–65	Law et al., 2022
Sewage sludge–algal biochar (Fe)	Pyrolysis + Fe	500–700	50–250	0.05–0.20	30–50	López-Miranda et al., 2023; Mian et al., 2023
Microcystis (bloom biomass)	Pyrolysis	500–600	10–60	0.03–0.10	30–45	Maddi et al., 2011
Chlamydomonas sp	Pyrolysis	450–550	5–25	0.01–0.05	30–45	Law et al., 2022

higher growth rate of macroalgae supports the satisfied production of algal biofertilisers. Furthermore, aquatic microalgae can be directly treated with different residues (animal waste, plant waste) or materials (zeolite, fly ash) for nutrient absorption to prepare feedstock biofertiliser, biochar, activated carbon, bioenergy, or metal capture (Osorio-Reyes et al., 2023).

In recent years, significant interest has arisen about waste from algal biomass, especially in the removal of excess nutrients and the recovery of valuable resources, such as metals and nutrients, by valorising them in algal biomass biochar. However, the nature and sources of algal biomass, the preparation pathways and conditions, and the metalloid removal capability of algal biochar require further in-depth examination and assessment (Ansari et al., 2026). Biochar produced from algal biomass derived from terrigenous plants has also been widely explored, yet biochar produced from algal sources has received significantly less attention. Biochar made from algal sources may nevertheless serve as an attractive resource in terms of potential functionalities and beneficent corrosion properties (Nguyen et al., 2023). Such biochar is thus amply qualified for a reduction in metal/metalloid ion speciation or concentration from aqueous solutions and other environmental compartments, such as sediments and soils. Environmental strategies for assisting the circular bioeconomy goals can therefore be readily established (Sarraf et al., 2024).

3.1 Microalgae versus macroalgae

Micro- and macroalgae exhibit contrasting growth patterns, physiological processes, and biochemical compositions, influencing their suitability as feedstock for biochar production. Microalgae possess a small structure and rapid multiplication potential, with growth cycles of days or even hours under optimal conditions (Abideen et al., 2022). Macroalgae, in contrast, develop at a slower rate over weeks, months, or years. Different metabolic processes are also prominent in these groups: microalgae utilise aerobic respiration, while macroalgae undergo anaerobic respiration. The spontaneous growth of microalgae without the addition of nutrients during biological wastewater treatment is another advantage of their use as bioresources (Borowitzka, 2016).

Table 1 delineates the key differences in growth, composition, and characteristics pertinent for biochar preparation from algal feedstock. Compared with lignocellulosic biomass, algal species typically possess a higher inorganic content, lower C–N and C–P

TABLE 3 Comparison of algal biochar with conventional adsorbents for metalloid/heavy-metal removal. Capacities and costs are ranges compiled from the studies included and are not pooled estimates; cost figures reflect feedstock and processing assumptions only.

Adsorbent	Capacity (mg g^{-1})	BET (m^2 g^{-1})	Cost (US$ kg^{-1})	Regenerability	Note/references
Algal biochar (unmodified)	5–50	< 5–120	0.003–0.8	Moderate	Low cost; lower capacity unmodified
Algal biochar (KOH/activated)	50–200	600–1500	0.1–1.0	Moderate	Activation boosts BET and uptake
Macroalgal biochar	10–100	< 5–120	Low	Moderate	High ash aids metalloids (Poo et al., 2018)
Microalgal biochar	10–120	5–1282	Low	Moderate	High SA when modified
Magnetic algal biochar	20–150	20–250	Low–mod	Good (magnetic)	Easy separation
Plant/lignocellulosic biochar	5–170	10–400	0.1–1.0	Moderate	Feedstock competes with other uses
Agricultural residue biochar	5–170	50–500	Low	Moderate	Widely available
Sewage sludge biochar	10–90	50–250	Low	Moderate	Contaminant carryover risk
Activated carbon (GAC/PAC)	50–250	800–1500	1–10	Difficult/costly	High capacity; costly to regenerate
Iron oxide nanoparticles	50–200	50–300	High	Variable	High affinity; recovery issues
nZVI/maghemite biochar	≤ 125 (As)	20–200	Moderate	Variable	Strong As(V) uptake (González García et al., 2025)
TiO_2 nanomaterials	10–80	50–150	High	Variable	Lower metalloid capacity
CeO_2 nanomaterials	20–100	80–200	High	Variable	Selective but costly
Fe–Ce binary/ternary oxide	100–300	100–250	High	Variable	Very high As capacity
Zeolites	5–40	200–600	Low–mod	Good	Cheap; low metalloid affinity
Layered double hydroxides	50–250	50–150	Moderate	Good	High anion exchange
Chitosan/biopolymer composites	50–100	Low	Moderate	Good	Tuneable groups (ChiFer, Sb)
Graphene oxide/CNT composites	50–300	100–700	Very high	Variable	High capacity; cost limits field use

ratios, and elevated mineral reservoir levels. These differences can confer advantages in biochar production and subsequent usage (Awasthi et al., 2026). However, for metal-doped biochar, the natural metal presence must be considered as preventing co-doping. Recent studies have highlighted the potential for waste-derived macroalgal biomass to serve as a biochar feedstock; indeed, pyrolysed biochars from *Sargassum* and *Gracilaria* spp. were confirmed as suitable in adsorbing ZnO and MgO while proving less efficacious for $NiSO_4$. Despite their lower growth rate and longer turnover time than microalgae, natural appearances and large quantities offer scope for bio- and valorisation-oriented approaches to utilising macroalgal biomass (Poo et al., 2018).

3.2 Sources of algal biomass

Algal resources for biochar production can derive from culturing, wastewater treatment, or natural growth. Large-scale cultivation typically assumes a controlled system that is not yet commercially viable (Sarwer et al., 2022). The main limitation for the mass cultivation of microalgae is their high land requirement, while for macroalgae, it is their large water salinity demand. Wastewater treatment and remaining algal bloom biomass, on the other hand, use the clearest advantages of algal technology for biochar production, making the processing of algal biomass in these two alternative ways considerably cheaper. In the former case, the algal biomass is produced under autotrophic conditions, using sunlight and nutrients from the wastewater. In the latter, the bloom biomass grows *per se* and, when reaching tipping point, endangers not only the water quality but also the surrounding ecosystem (Tan et al., 2023). Disposing of such excess algal biomass can be extremely costly due to all transport and removal steps.

Valorising that residue for the economic production of bioenergy/biochar during gasification/pyrolysis simplifies the valorisation concept. Several studies have discussed the pyrolysis of algal bloom biomass and proposed the need to optimise the process conditions (Osman et al., 2023). It is also important to notice that the physicochemical properties of algal biochar are very similar to those of lignocellulosic-derived biochar, which suggests that down-draft and fixed-bed gasifiers can be used for those biochar-producing species that nowadays have biochar production from lignocellulosic feedstock as a commercial reality (Binda et al., 2020).

3.3 Biomass composition and physicochemical properties

Data on the composition of algal biomass are essential for understanding its pyrolysis behaviour and predicting the properties of the biochar produced. Among the various

parameters influencing pyrolysis kinetics and char yield and the concentrations of lignin, hemicellulose, cellulose, and volatiles are the most important. Algal biomass has a high initial water content and a lower C–H ratio than lignocellulosic feedstocks (Vasudev et al., 2025). Its lower lignin content and higher content of easily decomposable components may negatively affect char yield and the structural integrity of the biochar produced. Conversely, biochar production may deplete a major share of the volatile components, resulting in a favourable increase in the C–H ratio. Algal biomass also has a lower ash content than lignocellulosic biomass, and the inorganic content is distributed homogeneously within the cells; such features have positive implications for pyrolysis. Recent studies show that the concentration of biopolymers in algal biomass can influence pyrolysis kinetics and char quality (Babatabar et al., 2022).

Biochar produced from algal biomass has specific advantages over biochar derived from lignocellulosic feedstocks in terms of environmental performance. Algal pyrograms eliminate odorous compounds, gaseous by-products may be less harmful than those produced during the pyrolysis of polysaccharides, and the processes run in an aqueous environment (Binda et al., 2020), thereby suppressing the volatiles. Furthermore, the high water content of algal feedstocks allows the integration of biochar production with biogas production through a co-digestion approach. Valorisation methods for wastewater-derived algal biomass are being developed, although their integration with metalloid sorption–removal processes remains largely unexplored (Ansari et al., 2026).

3.4 Advantages over lignocellulosic feedstocks

Algal biomass differs distinctively from lignocellulosic sources such as miscanthus, wheat straw, and wood. Factors include C–N ratios, mineral content, and elemental ratios for algal populations and pyrolysis conditions. Labour cost and CO_2 emissions during growth and harvest are relatively high with nitrogen fertiliser and minimal added phosphorus, while CO_2 compensation is rapid because of high growth rates (Maddi et al., 2011). Residual algal biomass from biofuels and biogas production requires disposal and often stimulates significant methane emissions. Algal char production from the formation of bioenergy and metalloid-removal synergies is a waste-utilisation strategy that supports circular economy goals (Ayala-Parra et al., 2017).

Cultivated algal biomass tends to achieve lower trace-element concentrations than waste products, residual algal biomass generally has poor thermal stability success, and leachate from residual biomass during pyrolysis or activation can impede char activity or benefit it, depending on heating methods and the metal species present (Lane et al., 2015). The removal of growth substrates and the invasion of macroalgae can impair hospital wastewater treatment, but treated water still meets effluent-discharge standards. Lowering microalgal biochar production costs through innovative strategic combination with other technologies can narrow the performance gap and support commercially viable deployment (Barwant et al., 2025).

3.5 Waste algal biomass valorisation

The potential of algal biomass as a feedstock for biochar production is complemented by the utilisation of algal wastes. These biomasses can be composed of algae cultivated specifically for biofuel production, algal blooms occurring in water bodies or in constructed wetlands, or algal residues following oil extraction (Sarwer et al., 2022). Since such residues are usually rich in both nutrients and lipids, they offer the possibility of integrating waste algal biochar production with the bioenergy sector. The removal of unwanted metalloids (e.g., As and Sb) from contaminated waters during the production or disposal process aligns with biochar production goals and enhances the ecological functions of algal-derived biochar (Priyanka et al., 2024).

Valorisation pathways involving thermochemical treatments of algal leftovers derived from biofuel production, or of reservoirs polluted by algal blooms, are presently being pursued. Waste algal biomass can therefore be sustainably valorised through several pathways, either completing the respective life cycles (circular economy) or integrating with others (waste/resource-minimising bioeconomy). Integration with bio-drying, pyrolysis, or gasification for energy recovery, without compromising negative emission objectives or the biomaterials' physicochemical properties, ensures their sustainability (Chen et al., 2017).

4 Production and engineering of algal biochar

A range of pyrolysis technologies are employed to produce biochar under different temperatures and heating rates; using various operational conditions, each pyrolysis route produces biochar with distinct surface properties and functionalities (Sharma et al., 2024). Hydrothermal carbonisation produces biochar with metalloid-affinity-enhancing properties owing to the nitrogen extracted from the protein component during carbonisation; the process is attractive for treating algal biomass with high ash/salinity content. Microwave-assisted carbonisation induces polarisation at the molecular level, resulting in enhanced surface reactivity, specific surface area, and pore volume and providing biochar with greater capacity to adsorb organic pollutants (Rasool et al., 2026). Algal biomass can also be gasified, thus enabling energy recovery with the complementary production of biochar that is likely to be suitable for environmental remediation. Torrefaction increases energy storage density and storage stability while yielding char that can be utilised in environmental remediation. Surface modification and activation further enhance sorption performance by increasing porosity and surface area, improving surface charge properties, and introducing additional adsorption sites. Recent studies have explored the development of nanomaterials and composite nanostructured biochars with advanced functionalities and synergistic effects (Fernández et al., 2025).

Algal biochar can be produced via pyrolysis, hydrothermal carbonisation, microwave-assisted carbonisation, gasification, or torrefaction. Each technique affects physicochemical properties and determines specific applications and engineering possibilities. The resulting biochar is subsequently enhanced using surface modification and activation strategies (e.g., KOH, H_3PO_4, and CO_2 activation)

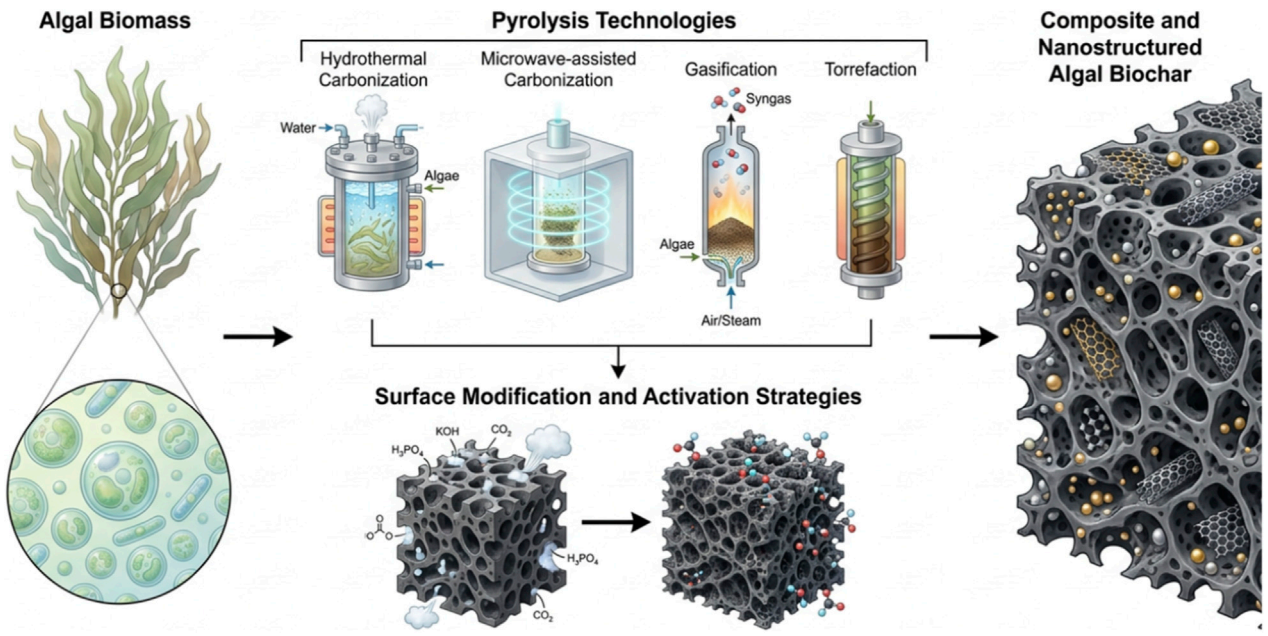


FIGURE 2
Conversion of algal biomass into advanced composite and nanostructured algal biochar.

to improve its porosity, surface chemistry, and functional groups, leading to the development of high-performance composite and nanostructured algal biochar for advanced environmental and energy-related applications (Figure 2).

Pit- and rotary-kiln processes afford biochar production on an industrial scale, and laboratory-scale set-ups enable the discovery of materials with complex structures/affinities (Yu et al., 2017). Post-production treatments enhance metalloids/metalloid-ions/organic-pollutant capture.

4.1 Pyrolysis technologies

Biochar derived from algal biomass encloses adsorptive properties of metalloids and involves waste remediation. These biochars are a partial alternative to activated carbon because of their lower price, even though the sorption capacity is usually lower than activated carbon (Tan et al., 2023). Two-step pyrolysis technology allows the production of biochar with high adsorptive capacity. A microwave synthesis process can promote the formation of porous structure on the surface. A two-step hydrothermal carbonisation method showed greater As and Se removal than activated carbon.

Biochar is produced by the thermal decomposition of organic materials under a limited supply of oxygen, with biochar being formed below 600 °C and carbonisation occurring above this temperature (Mandal et al., 2026). Several pyrolysis technologies have been used to synthesise biochar, which are reviewed in this section. The use of liquid media is an important area of recent research because it involves greater heat transfer than using gas media. A recent review analysed the different processes employed in these studies, including the use of stabilisers and the variation of the microalgae-to-liquid ratio (Uddin et al., 2018).

4.2 Hydrothermal carbonisation

The distinctive reaction conditions of hydrothermal carbonisation result in a unique char with a composition and morphology that enhances metalloid adsorption affinities. Hydrothermal carbonisation proceeds at elevated temperature under moderately acidic conditions in a liquid medium that serves as a reaction space capable of complexation with dissolved organics and reaction intermediates. The carbonisation of algal biomasses under such conditions minimises devolatilisation and concomitant losses in char yield (Wang et al., 2025). Algal residues produced from anaerobic digestion and other liquid slurry biorefineries have enabled co-digestion as well as integrated biogas and hydrothermal carbonisation processes. Hydrothermal carbonisation has also been used to valorise spent *Scenedesmus* biomass generated from high-rate sewage treatment.

Hydrothermal carbonisation generates a stable char with well-developed localised micro- and nanoscale porosity that, together with its ash composition, facilitates the binding of heavy metals and metalloids under redox-neutral conditions (Singh et al., 2022). The smaller voids serve as conduits for metallic contaminant species, while the interconnected microporosity enables surface electrostatic, coordination, hydrophobic, and hydrogen-bonding interactions in conjunction with a molecular-diffusion-assisted ion-exchange mechanism to reduce peak concentrations of Cd^{2+} and Ni^{2+} during exposure to a mixture of vichydroxylamine, iron-(III)-nitrate, sodium-thiocyanate, and mercuric-chloride (Wang et al., 2025).

4.3 Microwave-assisted carbonisation

The microwave-assisted carbonisation of algal biomass involves heat generation via microwave energy absorption by biomolecules

acting as dielectrics, transferring energy to neighbouring non-polar molecules until thermal runaway leads to thermal–chemical or thermal–pyrolytic decomposition. Rapid heating facilitates carbonisation and the formation of water-soluble components, deliquescing during treatment and hastening pyrolysis (Ray, 2022). The effects of experimental conditions (reaction time, temperature, surfactants, precursors) on structure and characteristics of micro/macro/mixed-scale biochar have been assessed, supported by analyses of attributes (porosity, surface area, composition, functional groups, zeta potential) related to sorption capacity toward diverse species. The products exhibited high surface area and a uniform porous structure, enhanced anion/cation absorption characteristics, and retention abilities toward varied ionic metalloids (Ghora et al., 2025).

Addition of KOH or K_2CO_3 during carbonisation enriches biochar with abundant micropores and enhanced iodine adsorption capacity and electrochemical performance. The characterisation of biochar produced from *Nannochloropsis* sp. by K_2CO_3-assisted microwave-assisted process revealed exceptional nitrogen storage ability owing to specialised porous morphology. The adaptation of wastewater-derived biochar for odorous gas treatment achieved a balanced So_2CO_2 absorption ratio and notable biogenic volatile compound removal capacity, detecting dual enrichment mechanisms (ozone: chemical ratio, N_2O: ionic mechanism) of layered aluminosilicate-zinc/iron-biochar composites in gaseous removal. Microwave-assisted biochar derived from *Chlorella pyrenoidosa* displayed a competitive adsorption of reactive dyes (Kusmayadi et al., 2025).

4.4 Gasification and torrefaction

Gasification and torrefaction also present promising pathways for converting algal biomass into energy-rich products and, consequently, into biochar. Gasification enables the transformation of biomass into synthetic gas—mostly gaseous hydrogen and carbon monoxide—rich in energy and suitable for further deoxygenation to obtain fuels and chemicals and/or as a substrate for the Fischer–Tropsch synthesis, which produces fuels based on liquid hydrocarbons (Saleh et al., 2026). Gasification aims to promote endothermic partial oxidation reaction to obtain a gas, with lower yield of solid residue product than pyrolysis. Algal biomass is suitable for gasification as its high protein content is a source of nitrogen and sulphur that can jointly be converted with carbon into valuable chemicals such as ammonia and hydrogen sulphide. Their conversion into hydrogen-rich gas also leads to a biochar byproduct of lower energy contents but with advantageous characteristics. Algal biochar is an attractive inorganic catalyst, while the application of alumino-silica minerals leads to higher-quality gas production with fewer tar contaminants (Arena, 2012).

Torrefaction promotes HS and CO_2 emissions to obtain a solid product of higher energy density and with a structure close to coal—a suitable precursor for clean coal technologies. Torrefaction modifies the structural properties of algae and improves the carbon content of biochar. A suitable temperature range for these modifications is 220–260 °C, as torrefaction at lower temperatures hinders the removal of alkalis and transition metals, jeopardising the application of these algal chars in the sorption of NO_2; at higher temperatures it degrades the structure too much (Gan et al., 2018).

4.5 Surface modification and activation strategies

Various strategies have been developed to enhance the metalloid-binding capacity of algal biochar through surface modification and activation. Surface area can be amplified using mineral salts via *in situ* or *ex situ* treatment, while biochar also serves as a support matrix for zeolite and activated carbon. The introduction of amines has further accelerated removal kinetics. Remediation performance can also be improved by combining biochar with nanomaterials such as functionalized iron oxide loaded onto activated carbon derived from *Salvinia molesta*. Eggshell biochar impregnated with Fe–Mn and Fe–Zn–Al composites has successfully catalysed the Fenton-like degradation of dyes and supported the effective removal of metalloids and heavy metals (Rocha et al., 2024).

Current studies have increasingly demonstrated the potential for highly effective and promising composites, nanocomposites, magnetic composites, and composite hydrogels to treat metalloids or multiple pollutants simultaneously. However, relatively few reports exist on the practical use of nanomaterial-based algal biochar composites. Because nanomaterials are broadly applied in many industries, it is crucial to determine their influence on algal biochar adsorptive capacities and bacterial activity and to certify compliance with environmental safety criteria (Parthipan et al., 2026).

4.6 Composite and nanostructured algal biochar

Emerging studies have detailed biochars produced through hybrid sequences that combine pyrolysis with the synthesis of metal oxide, sulphur oxide, or phosphate nanostructures and composites using metal-chloride-coated or phosphonated algal materials as precursors (Weidner et al., 2022). Concerns regarding contaminants in biochar derived from sewage sludge and their implementation as adsorbents and activators of environmental processes have fuelled research focused on composite nanostructures or sorbents. Starch was incorporated with algal sludge during pyrolysis to enhance graphene and metallic N dopant synthesis. Zirconium-algal-sludge nanocomposite beads have demonstrated utility for the sorption of Cr(vi) ions from aqueous media. Phosphorus–sulphur compound modified sewage sludge-algal biochar removed As(V) and influenced As(III) distribution. Algal biochar coated with iron–zinc bimetallic oxide effectively transformed Cr(vi) and Ni(ii) into respective low-toxicity states. The two-step growth of Mn_3O_4 on algal sludge biochar facilitated sorption and catalytic reduction of Cr(vi) to Cr(iii). Magnesium hydroxide–phosphorus pentoxide additives produced phosphorus–sulphur promotional effects within reconstructed phosphoric acid activated algal sludge biochar (Mian et al., 2023). An efficient single-step synthesis method combined iron oxide and sewage sludge–algal biochar activation to obtain a ternary magnetic nanocomposite with enhanced As removal.

Nanostructures synthesised from algae may be employed as substitutes or activators for environmentally sensitive materials. A review detailed upcycled nanostructures derived from algal biomass,

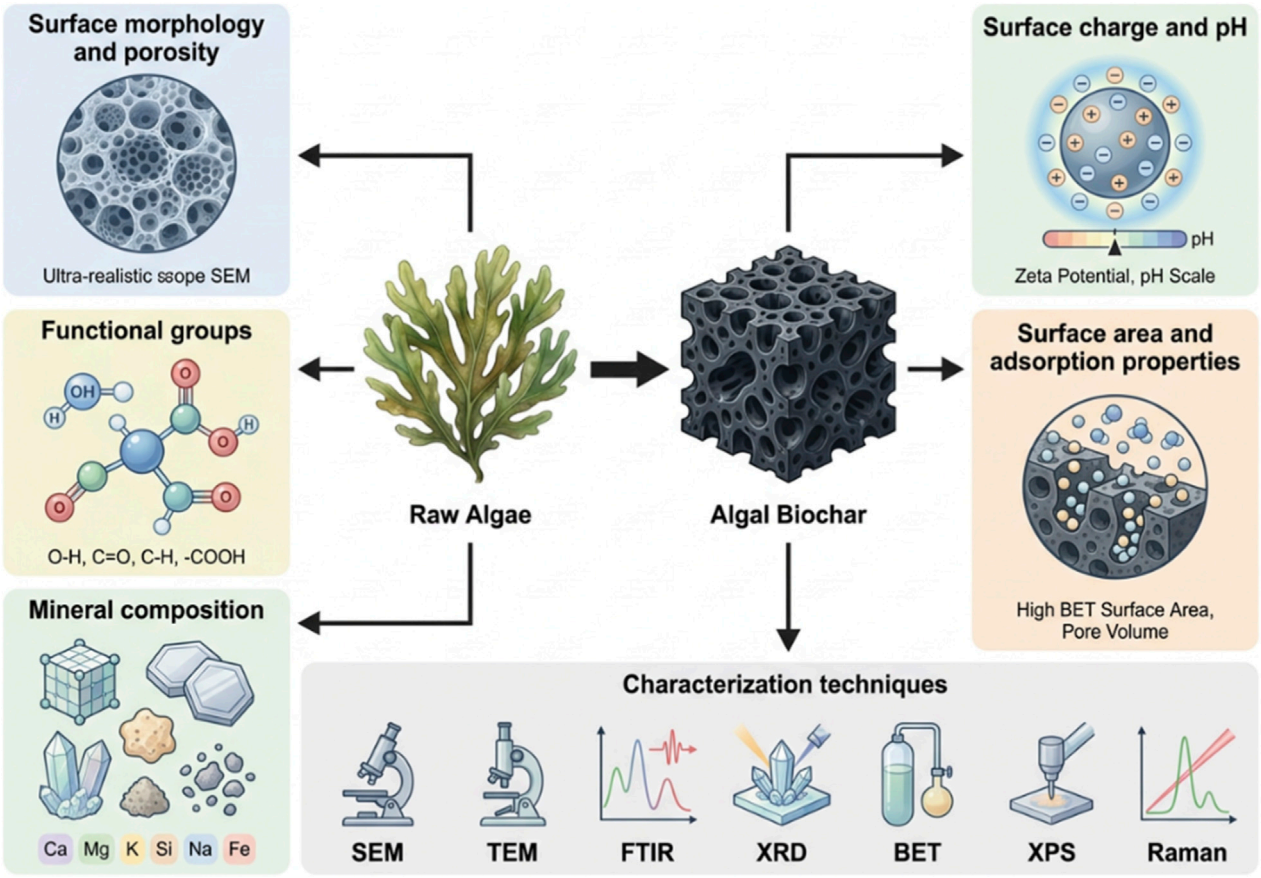


FIGURE 3
Physicochemical characteristics and analytical characterisation of algal biomass and algal biochar.

porous-algal-carbon-modified composites for waste remediation, and nano-adsorbents for water applications that were affordable, sustainable, efficient, and nontoxic. Algal sludge pyrolysate acted as both low-cost stabiliser and bio-surfactant in producing nanoparticles with a high active composition suitable for photocatalytic applications (López-Miranda et al., 2023).

5 Physicochemical characteristics of algal biochar

Algal biochar has been successfully employed for metalloid removal from contaminated systems, incorporating two key insights: the structure of the sorbent and its interactions with targeted metalloid species. Several studies have investigated the surfaces of algal biochar produced through various processes such as fast pyrolysis, slow pyrolysis, microwave-assisted carbonisation, hydrothermal carbonisation, gasification, and torrefaction. However, acid/base properties, the presence of surface functional groups, mineral composition, specific surface area, pore volume, and pore size distribution have yet to be systematically examined (Mondal et al., 2024). Despite its low carbon content, algal biochar may offer substantial affinity for metalloids, boron, and phosphorus to be released in non-negligible quantities during the aging of biochar in soil, potentiating secondary pollution in long-term applications. A thorough characterisation of physicochemical properties in the context of metalloid removal is a fundamental basis for interpreting performance in aquatic, sedimentary, and terrestrial systems.

Surface morphology, porosity, investigation of the surface charge, point-of-zero charge, the effect of pH on sorption behaviour, the identification of functional groups, and the discussion of mineral composition in relation to their role in influencing binding phenomena are crucial aspects related to removal mechanisms. The use of main characterisation techniques (SEM, TEM, FT-IR, XRD, BET, XPS, and Raman spectroscopy) have also addressed (Figure 3). The findings provide a basis for understanding the affinity of algal biochar for metalloid species, paving the way for the safer environmental application of biochar (Geng et al., 2011).

5.1 Surface morphology and porosity

Surface morphology and porosity are vital for determining the adsorption capacity of any material; they relate directly to sorption kinetics and equilibrium. The interaction of external and inner surfaces with metalloids will significantly affect binding. Microscopic techniques are widely used to assess surface texture and morphology, pore structure, and size-distribution (Wang et al., 2020).

Scanning electron microscopy (SEM) results indicate that most algal biochars possess an irregular three-dimensional structure. Flattened and fragmental surfaces are typical, although some surfaces are intact and still maintain a viable algal structure. Engulfed sites with irregular shapes also occur, implying the uneven distribution of internal structures. The porous structure is helpful for metal ion uptake. Transmission electron microscopy (TEM) further reveals rough, wrinkled surfaces with pores 2–5 nm wide induced by N_2-doping (Li et al., 2026).

Algal biochar has lower total pore volumes than lignocellulosic-derived biochar but possesses capacious meso/large pores that improve bulk permeability and accessibility. The small average diameter is likely a result of low-temperature pyrolysis. Algogenic biochar produced at TC > 400 °C is less porous, leading to smaller pore radius and volume, but small pores are more favourable for ion diffusion. High-temperature pyrolysis above 800 °C impedes the development of mesoporous channels while favouring larger pores. High oxygen and nitrogen contents in biochar surface functional groups will be better for metal sorption (Binda et al., 2020).

5.2 Functional groups

Algal biochar chemically comprises a range of functional groups on its surface. The effect of these functional groups in binding to metal and metalloid species in the aqueous phase has been well documented. Algal biochar is known to contain carboxyl (-COOH), carbonyl (C=O), hydroxyl (-OH), and phenolic (-ArOH) functional groups. FT-IR analysis has characterised the surface of algal biochar and the presence of change in functional groups, thus explaining the adsorption mechanism involved in binding the metalloids (Nguyen et al., 2023). FT-IR characteristics reveal that hydroxyl, carboxylic, and tartaric complexes are involved in the absorption spectra of algal biochar. Additionally, Raman spectroscopy studies confirm the extensiveness of the porosity and surface connectivity of algal biochar. These provide accessible active sites, hydroxyl groups support hydrogen bonding and surface complexation, and C=C domains stabilise the surface and may promote precipitation, all of which favour metalloid uptake at low equilibrium concentrations. The Raman intensity ratio I2/I1 has also been correlated with the removal efficiency of ionic metal and metalloid species by algal biochar systems (Kumar et al., 2024).

Sb, As, Se, and Te removal is mainly controlled by surface complexation and electrostatic attraction between positively charged protonated surface sites and negatively charged oxyanions. The presence of hydroxyl functional groups on biochar surface contributes to H-bonding. The positively charged surface of biochar at low pH favours the adsorption of anionic oxyanions As species in solution. The interaction is essentially a redox reaction with negative surface charge facilitating the transfer of electrons from biochar surface to oxyanions. Precipitation/co-precipitation is the significant mechanism of Te ion removal from the aqueous phase with biochar where significant amount of ash content is present. The metallic content of the ash component plays a vital role in Se and Te removal since, during removal, it enhances the degree of precipitation (Kińska et al., 2024). The characterisation of surface charge on biochar is vital during the removal action, as preference to OH- and Cl-ion availability govern the composites' surface charge and enhances the adsorption of metalloids. Algal biochar's removal capacity is positive for As^{5+} ions and negative for As^{3+}.

5.3 Mineral composition

The mineral composition of algal biochar has attracted considerable attention recently because the metalloids of greatest environmental and ecological concern—As, Se, Te, and Sb—are more efficiently removed by algal than by plant-derived biochar (Johansson et al., 2016). Metal oxides and hydroxides are key oxide/metal categorisation components that physically and chemically adsorb metalloids. In general, large amounts of metal oxides (particularly iron oxides), alkaline elements, and cationic exchange capacity also greatly enhance the metalloid-removing ability of biochar. Inherent or synergistically formed metal oxides (particularly iron-based oxy- and hydroxides) have ionic radii that favour the adsorption of anionic metalloids. For example, in the case of arsenic, Fe^{3+}, the most widely studied cationic competitor, is chemically stable or electrostatically bonded with AsO^{-43-}, but AsO^{-33-} is more favourably adsorbed (Ngo et al., 2023).

The ash mineral composition of algal biochar plays an important role in the uptake of metalloids such as As and Sb, and these interactions have been little studied. A proper analysis requires detailed knowledge of mineral content, point-of-zero charge, and charge properties, with separate examination of metalloids (both anionic and cationic) as well as the utilisation of the Langmuir and Freundlich isotherm models. These elements can also undergo adsorption/desorption reactions. Traces of other minerals in nanoscale or composite applications can further enhance affinities for metalloids (Li et al., 2025).

5.4 Surface charge and pH

The electrostatic force of attraction between charged surfaces is pivotal in driving adsorption onto charged hosts. Metal metalloids, particularly of the As group, are often present in anionic, neutral, and cationic forms depending on the pH of the solution, which leads to distinct tendencies with respect to binding on biochar surfaces. Moreover, a consideration of the point-of-zero charge of the biochar is essential in understanding trends across metalloids, and surface charge and pH can influence speciation and competitive tendencies (Parlayıcı et al., 2025). The pH-dependent behaviour of biochar toward As group elements and Se must also be understood in terms of speciation, given that these metalloids can exist as oxides as well as in hydrosoluble form. When pyrite is present as a mineral constituent, the pH of the environment can either favour or disfavour dissolution and therefore the release of soluble As for sorption on biochar. It also has to be borne in mind that the point-of-zero charge of biochar decreases with increasing pyrolysis temperature, resulting in an increased tendency to adsorb negatively charged species (El-Naggar et al., 2018).

For thermally activated biochars produced at high temperature, their practical use for metals removal may be limited when the solution pH is lower than 5, since the activated carbons are mainly negatively charged at natural pH value, thus hindering their adsorption of anions. In an agro-ecological context, the achievement of a pH ≤ 5 in the soil during the growing season may limit the ability of activated carbon applied in soil to sequester

As. In the specific case of Al-doped carbon prepared through chemical activation, the surface charge is significantly affected by the pH of the solution and shows a particularly sharp change over an acidic range of 3–5 with an isoelectric point at around pH 3.5, becoming positive below this pH (Xu et al., 2021).

5.5 Surface area and adsorption properties

Surface area and adsorption capacity strongly influence sorption kinetics and equilibrium, determining overall removal efficiency during the interaction between sorbent and solute. Several studies have established a positive correlation between the surface area of algal biochar and its adsorption capacity for metals and metalloids, particularly As. Algal biochar generally exhibits lower specific surface area values than other biochars, yet it often outperforms activated carbon in terms of effectivity, especially regarding the sorption of metalloids with relatively low ionic radius and hydration energy (Sekar et al., 2004). Such diminished surface area is likely offset by the specific interaction patterns of algal biochar with metal/metalloid species and the preparation step of the algal feedstock, specifically by the treatment with acid prior to pyrolysis. H_3PO_4 activation can play a key role in enhancing the surface area and pore structure and in increasing the As_2O_5 adsorption amount. Table 2 summarises representative pyrolysis conditions and the resulting physicochemical properties of algal biochars reported across the studies included.

Adsorption isotherms express the affinity of a sorbent for a given adsorbate at equilibrium and characterise the effect of concentration on the removal kinetics. Generally, for a predominant part of biosorbents, including algal biochars, the experimental data matches well with the Langmuir and Freundlich isotherm models, thus indicating the predominance of monolayer formation on a surface with a finite number of adsorption sites. Both the adsorption energy indicated by the Langmuir parameters and the Freundlich heterogeneity factor reflect the higher affinity of algal biochar for As than for other metalloids. Key experimental results are comprehensive in their support that algal biochar systems, independently of the preparation method, generally exhibit superior As sorption capacity to the reference Pac, AlgNat, and DDMBC.

5.6 Characterisation techniques (SEM, TEM, FT-IR, XRD, BET, XPS, and Raman)

The previous subsections described the physicochemical properties of algal biochar of relevance to metalloid sorption. This subsection briefly identifies the principal characterisation techniques employed in this area of research. SEM and TEM reveal surface morphology and meso–macro-porosity (SEM) and nano-structure features (Kamal-Eldin et al., 2020). Fourier-transform infrared spectroscopy (FT-IR) identifies the variety of polar functional groups in biochar samples, the presence of which are responsible for binding metalloids. Powder X-ray diffraction (XRD) analyses the bulk mineral composition and governs the sorption mode of chemical species; for example, the predominance of clay minerals favours electrostatic attractions, while oxy- or phospho-silicates assist in anion exchange. The Brunauer–Emmett–Teller (BET) technique quantifies total surface area and mesoporosity, indices correlated with the overall sorption capacity and the expression of Langmuir isotherm behaviour (Saitzek et al., 2008). X-ray photoelectron spectroscopy (XPS) examines the chemical states of certain atoms in the outer regions of a sample and provides an overview of oxidation states and valences. Raman spectroscopy delineates the relative contribution of the D and G bands, which signify defects and disorder, and graphitic structure, respectively (Krishna and Philip, 2022).

6 Sources, distribution, and environmental behaviour of metalloids

Metalloids such as As, Sb, Se, and Te occur naturally in oxidative environments, often in crystalline forms that render them highly stable and relatively inert. Redox-active metalloids, such as As and Se, exist in multiple oxidation states and can undergo bio-geo-chemical transformations. Consequently, environmental concentrations and species of metalloids are primarily influenced by anthropogenic activities (Medina-Cruz et al., 2020). Mining, burning of fossil fuels, smelting, and other industrial processes introduce potent emissions to the environment, while the application of agricultural inputs associated with natural weathering contribute lower but more diffuse release over geospatial scales. These natural and anthropogenic sources determine the distribution, transport, and settlement of metalloids within environmental compartments. Therein, the metastability of redox-active species permits speciation shifts and variation in mobility, bioavailability, and ecological effect (Wen et al., 2022).

The most toxic and prevalent metalloid is As. It occurs naturally in groundwater largely, because As-rich minerals are present in rocks that are subject to weathering, although human activities have also disturbed the natural flow of As. The mining of As, its unintentional release through the mining of other ores, the use of As-based products, and the combustion of fossil fuels are significant sources of environmental As. Sb speciation is determined by redox conditions, pH, and the concentration of other ions in solution. Se is distinctive among metalloids because several of its forms are directly relevant to biological processes, entering the Se cycle via different pathways and then being transferred, bioaccumulated, and biomagnified. Recent mass budget estimates indicate that global geological weathering and Chinese anthropogenic inputs dwarf those from other sources; for other regions, natural input–removal patterns must be better resolved (Herath et al., 2016). Information on the occurrence and trends of environmental Te is still incomplete, but it has been added to the list of metalloids needing close monitoring because of its emerging environmental relevance.

6.1 Arsenic

By far the most recognised metalloid pollutant, As occurs in various valence states and species; the most abundant forms in environmental settings are arsenite (As(III)) and arsenate (As(V)), the latter predominating under oxic conditions and the former in anoxic environments. Numerous anthropogenic activities contribute As to terrestrial and aquatic systems. Mobilisation occurs from mining, metal smelting, and inorganic fertiliser use, as well as from the reductive dissolution of Fe and Mn oxides in anoxic soils and sediments. As undergoes biogeochemical cycling

via methylation and related transformations; methylarsenicals, whether organic or not, are an emerging focus of research (Patel et al., 2023).

As is toxic to all living organisms, with chronic exposure having profound effects on human health. Its compounds are primarily carcinogenic and teratogenic, though non-cancer-related effects also occur. Soil and groundwater As contamination are significant concerns for many countries. Safe drinking-water regulations, in place for over a decade in the European Union, Australia, and the USA, mandate total As levels below 10 μg/L due to heightened cancer risk and developmental problems from long-term exposure. In other parts of the world, As concentrations often far exceed these limits (Genchi et al., 2022).

6.2 Antimony

Sb is a toxic metalloid that can exist in various oxidation states (−III, 0, +III, and +V), with oxidation state + III being its predominant form in the environment. Its main sources of release into the environment are mining and metallurgical processes, waste incineration, coal combustion, and industrial processes, while the main removal processes are photoreduction and precipitation in aquatic media and adsorption onto the surface of solid-phase particles. Recent studies on the occurrence, distribution, and environmental fate of Sb in aquatic systems and soils provide new insights into the potential environmental pollution caused by Sb contamination (Li et al., 2016).

6.3 Selenium

Se occurs in inorganic (particularly selenate SeO_2^{4-} and selenite SeO_3^{2-}) and organic forms (selenium–amino acids and selenoproteins). Mining activities, acid-rock drainage, and the application of fertilisers and pesticides are major natural and anthropogenic sources of Se. Selenite is comparatively more mobile than selenate, especially in acidic soils, as its adsorption by most minerals is at a minimum at low pH. Relevant to pollution trends, selenite tends to be taken up by plants more readily than selenate. Se exhibits several redox states—namely, −2 (hydroselenide), +2 (selenite), +4 (selenate), and +6 (perselenate)—that interconvert in biochemical, geological, and photochemical processes. A variety of oxidation states and complexes contribute to Se's mobility, bioavailability, and potential for toxic effects (e.g., Se-induced malformations in plants) (Kieliszek, 2019).

6.4 Tellurium and emerging metalloids

Te is a rare metalloid that has become a focus of environmental studies owing to its toxicity, increasing anthropogenic input, and growing global demand. The speciation of Te in the environment remains poorly understood, and its impact, particularly at trace levels in aquatic ecosystems, has been largely overlooked. Other metalloids, such as germanium and polonium, also require increased attention owing to their toxicities, elemental scarcity, and/or environmental mobility (Filella et al., 2019).

Te has generally been studied from a mineralogical perspective, with its presence in natural waters only recently documented. The parameter "tellurium" has not been included in the monitoring programs of water quality established by several worldwide agencies. With tis industrial use increasing exponentially, the development of Te extraction technology has become an important area of research in South Korea, Japan, and China. Other emerging metalloids include boron, bismuth, germanium, lanthanum, polonium, and thallium. Although they generally occur at low concentrations in the environment and possess limited bioavailability, they are nevertheless toxic to living organisms, especially at high concentrations (Chung et al., 2024).

6.5 Transport, speciation, and bioavailability

The transport, speciation, and bioavailability of metalloids in aquatic environments, soils, and sediments are processes of critical importance for assessing ecological and human health risks. In freshwater, metalloids can be transported as dissolved species, colloids, or suspended particulates, while their forms in soils and sediments remain closely related to pore-water equilibrium. In addition to transport, the survival of organisms and environmental risk also relies on bioavailability, which governs the uptake of contaminants by specific receptors (Chapman et al., 2003). The bioavailability of metalloids is affected by the characteristics of target organisms (e.g., uptake mechanisms, detoxifying systems, and presence of accumulating or tolerant species), the physical and chemical properties of contaminated media (e.g., surface charge, oxidation status, and bulk concentrations), and the physiological conditions (e.g., temperature, redox potential, oxygen concentration, and toxicity of cations) of the receiving environment. Moreover, the changing equilibrium among contaminant assemblages for different forms can lead to variation in bioavailability. Transport, speciation, and bioavailability form the basis of all biological uptake and accumulation (Tang et al., 2024).

In soils and sediments, the transportation, speciation, and bioavailability of metalloids determine how organisms interact with them. Distribution predictions based on thermodynamic concentrations should be viewed with caution because not all forms are bioavailable and not all environmentally important assemblages are acknowledged. In addition to the equilibrium reached between metalloids and the environment, the order of speciation can be modified by the suffering species (Chapman et al., 2003).

7 Algal biochar–metalloid interaction mechanisms

The diverse physical and chemical characteristics of biochar have been attributed to sorption interactions with metalloids on the surface, in pores, and via infiltration into the bulk material, as well as on inorganic or mineral-like constituents. The electrostatic attraction of metalloid species, surface complexation linked to surface functional groups, ion exchange, precipitation facilitated by ash or mineral components, and redox transformations that influence speciation are among the mechanisms proposed. Hydrogen-bonding forces complement these various mechanisms, with pore-filling effects and the contribution of mineral constituents and impurities also considered (Wang et al., 2017).

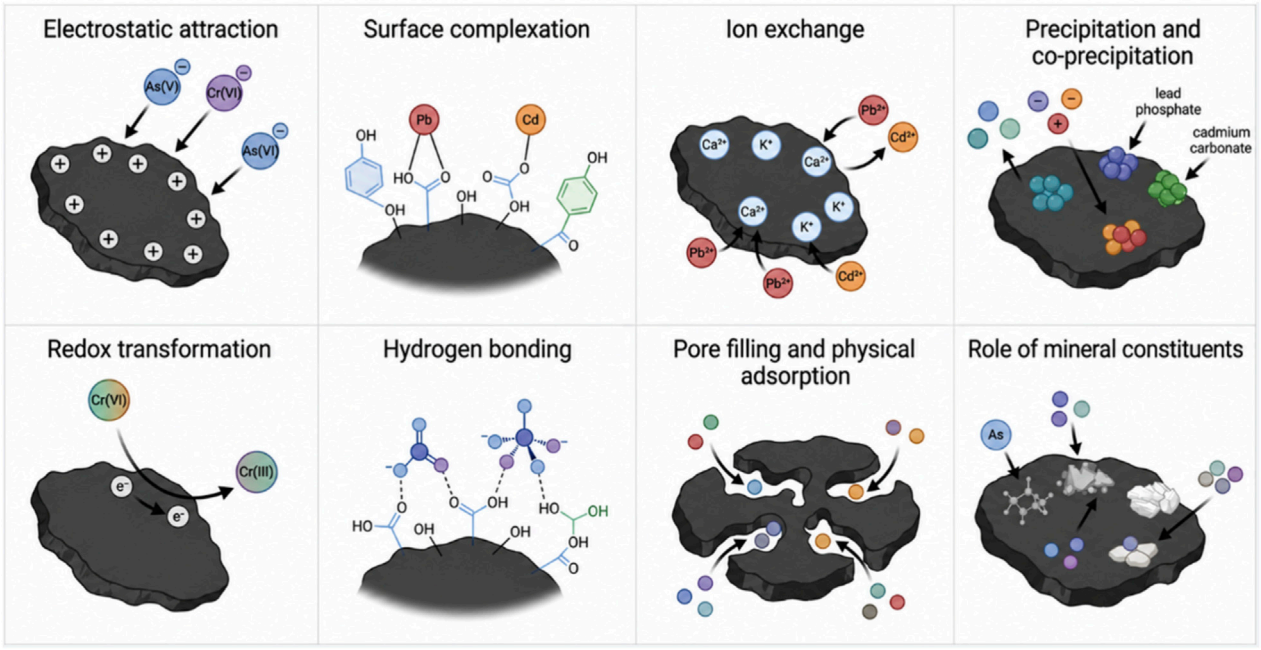


FIGURE 4
Illustration of the major mechanisms involved in heavy metal and metalloid immobilisation and adsorption by algal biochar.

The importance of these mechanisms relative to biochar composition, with specific minerals or ash fractions shaping the nature of interactions, has been highlighted across studies. Electrostatic attraction appears to predominate for anionic metalloid species, whereas precipitation mechanisms are expected to be particularly relevant for positively charged metalloids such as Te(IV). Furthermore, both mineral content and surface charge density are recognised as influencing factors, with lower point-of-zero charge facilitating greater attraction of negatively charged metalloids (Guo et al., 2023). The adsorption process occurs through multiple synergistic pathways, including (i) electrostatic attraction between charged biochar surfaces and metal ions, (ii) surface complexation with oxygen-containing functional groups, (iii) ion exchange with inherent alkali and alkaline earth metals, (iv) precipitation and co-precipitation of stable mineral phases, (v) redox transformation of redox-active contaminants, (vi) hydrogen bonding with surface functional groups, (vii) pore filling and physical adsorption within the porous biochar matrix, and (viii) interactions with mineral constituents present in the biochar (Figure 4).

7.1 Electrostatic attraction

Electrostatic interactions are critical for the binding of metalloid species to biochar surfaces. The surface charge of biochar is influenced by the pH, leading to variations in surface charge density according to the pH-dependent dissociation of functional groups. The point-of-zero charge (PZC) represents the pH at which the biochar's surface bears neither a positive nor a negative charge. The surfaces of biochar and metalloids carry opposite charges at pH levels below the PZC; therefore, electrostatic attraction governs the binding process. For example, the removal of As(V) from aqueous solutions using various biochars has been attributed to electrostatic attraction. However, charge density is not the sole factor determining performance; other characteristics of the biochar, the nature of the ion, and the presence of other ions in solution also play important roles (Lee et al., 2022).

Electrostatic attraction is only one of several possible binding mechanisms between algal biochar and metalloids. Charge density is not the primary factor influencing the removal of As by biochar; rather, the extent of reduction of Cr(VI) appears to be more closely related to the specific surface area of the biochar. Unlike anions, the binding of cations is affected by the total concentration of competing cations in solution.

7.2 Surface complexation

Surface complexation processes represent important mechanistic pathways for metalloid–algal biochar interactions. While the participation of surface functional groups in biochar–metalloid complexation has been implied in numerous studies, experimental evidence that identifies specific groups or functional moieties involved remains scarce. The theoretical considerations presented below shed further light on this aspect (Liu et al., 2025).

Metal binding to functional groups occurs primarily through either Lewis acid–base reactions or electrostatic attraction between oppositely charged species. At typical environmental pH values, arsenate and tellurate anions, as well as positively charged forms of Sb and Se, are expected to bind to negatively charged surfaces of unmodified or NaOH-activated biochars through electrostatic attraction. Electron-accepting metal ions such as Hg^{2+} and Cu^{2+} are anticipated to interact with electron-donating surface sites (e.g., –O–, =O) via Lewis acid–base reactions. Surface species such as Ti–OH, Al–OH, Fe–OH, and $–PO_4$ contribute to Hg^{2+} binding and

reduce its bioavailability in solution. The binding of As and Se oxyanions may also occur via acid–base interactions with Ti–OH and Al–OH moieties. Individual pyrolysis-derived groups are often considered, but a consolidated mechanistic understanding remains elusive (Silva et al., 2018).

Infrared (IR) spectroscopy examinations of the As(III)-algal biochar complex indicate that band shifts and changes in relative intensities of specific peaks relative to the pure biochar spectrum were consistent with As(III) bonding to–O–, –C–OH, and possibly = O groups. The binding of selenite, another important oxidative form of Se, was ascribed to unsaturated groups (vinyl and carbonyl) and atomically- or hydroxyl-terminated carbon surface structures. Speciation trends suggested that Se(IV) species with higher bonding capacity bind preferentially, but to a lesser extent than nitro and nitroaromatic groups, including $–NO_2$, –NO, and –N=O–components of the biochar surface. A distinct signature of Se–O stretching modes in the 800–1050 cm^1 region was also observed (Zhang et al., 2020).

7.3 Ion exchange

Ion-exchange processes are also relevant to the uptake of metalloid species. The mobility of metalloids from surface sorption sites can be inhibited by the preferential binding of counter ions in solution. In general, an increase in removal efficiency can be expected for cationic species in the presence of anionic species and *vice versa*. The recent literature suggests that the removal of Sb(III) and Sb(V) and of As(III) by a mixed-biochar adsorbent is favoured in the presence of HPO_4^{2-} and $H_2AsO_4^-$ ions, respectively. The positive effect of HPO_4^{2-} on Sb removal may be enlarged even further in the presence of $H_2AsO_4^-$ in solution, showing the complexation behaviour of mixed ion species. Such specificity in competitive ion removal possibly offers an advantage over commercial activated carbon (Caporale and Violante, 2016).

7.4 Precipitation and co-precipitation

Reports have documented the successful removal of As, Se, Sb, and bismuth metalloids in wastewater by biochar generated from various wastes. Mechanisms for these removals primarily include electrostatic attraction, surface complexation, and ion-exchange processes, as well as possible hydrogen-bonding contributions and pore-filling processes. Mineral components from the biochar, such as oxy-acids, sulphates, sulphites, and iron oxides can also serve as supporters to link with these metalloids. It is imperative to further elaborate the roles of these mineral components on the interaction mechanisms (Abhishek et al., 2023).

The precipitation or co-precipitation of metalloids within bioderived yeasts and bacteria has been reported. Although proposed for algae, the ability of algal biochar to incorporate metalloids via precipitation or co-precipitation remains largely unexplored. Such processes, in addition to interactions with ash and mineral components, may also contribute to the retention of metalloids from contaminated water, thereby enabling these algal-biochar–metalloid solutions to be deployed in various industrial applications. Algal biochar is generally less popular for metalloid removal than other types of biochar or carbonaceous materials (Son et al., 2018).

7.5 Redox transformation

Oxidation-reduction (redox) processes can influence metalloid speciation, mobility, and sorption. Redox transformations are of particular relevance to Se, whose aqueous speciation is pH-dependent in the range of conventional natural water and wastewaters. The fate of Te may also be affected by redox conditions. Speciation changes may therefore affect transport processes, adsorption on biochar surfaces, and bioavailability in aquatic and sediment systems. Notably, redox conditions in the sediment–water interface govern the mobility of several metalloids, with sharp concentration–depth profiles associated with redox transformations occurring over short distances. In oxidising environments, As adsorbs onto Fe and Mn oxides, and the release of these metalloids into ground and surface waters is less probable (Cooper et al., 2006).

Redox transformations may additionally affect Sb in oxic marine sediments and impact its release in saline environments. Attention must therefore be given to the natural redox condition of water or sediments, as the extent of sorption may differ from that in the source water and influence the ability of biochar–wetland systems to remove metalloids. Boardman et al. (2026) observed that the extent of Sb or Se removal tended to be substantially lower than for As or aqueous SHG-modified ACB. Such variations reflect differences in chemical mobility and solid–solution partitioning rather than selectivity on the part of the chemical sorbents. Hydrogen bonding may also play a role, contributing to Se interaction with acetyl–Zn–ACB (Wu et al., 2022).

7.6 Hydrogen bonding

Hydrogen bonding between algal biochar and metalloids can occur. Unlike surface complexation or other chemical mechanisms, this involves the electrostatic attraction of a protonated metal (or metalloid) species by an electronegative element (oxygen or nitrogen) that holds hydrogen atoms. Such attractions may not be the main adsorption mechanism. However, they can contribute significantly to the binding of some asymmetrical metalloids (such as Sb) when travelling as positive ions and appear to be an important factor in the precipitation and co-precipitation of surface morphologies or components that present a bound H_2O layer (Pahlavan et al., 2024).

In these reactions, water acts as a lubricant to enhance surface morphologies that are generally unfavourable for complex formation, and the electronegative component participating in hydrogen bonding is simply responsible for the stable support of the protonated metal (or metalloid) species shared by two or more negatively charged atoms of hydrogen.

7.7 Pore filling and physical adsorption

Pore filling and physical adsorption are less significant mechanisms that contribute to the interaction between algal biochar and metalloids, but they cannot be entirely disregarded. Due to their relatively large ionic radii, metalloids such as As and Se require a relatively large pore structure for removal by pore filling. Consequently, the adsorption of these species onto biochar with a more developed pore structure may occur through a pore-filling

mechanism. The dominance of an activated carbon mechanism over pore-filling is expected given the fact that the surface area of animal-derived activated carbon is often considerably larger than that of biochar without a large number of pores (El Messaoudi et al., 2025). In general, physical adsorption is considered to be less important than the mechanisms previously outlined. Nevertheless, although the initial weak Van der Waals attractions cannot be accurately described by conventional surface diffusion theories, they have been demonstrated to play an important role in metal adsorption. Cheng et al. (2021) recently proposed a dual-pore flow model for the physical adsorption of ions where the interfacial mass transfer rate coefficient depends not only on the concentration gradient of the species but also on the concentration difference between the primary and secondary pores.

Consequently, when a solution with a certain concentration comes into contact with biochar possessing a considerably lower concentration of an ion to be physically adsorbed, mass transfer will occur in the same way as for a solute diffusing from a primary pore into a corresponding external bulk solution; however, for a contrary concentration gradient, the diffusion velocity will be smaller. Furthermore, although the final state is determined by the relative concentrations, the flow paths into the inner portion of the particle and out of the particle also will be affected by the concentration differences. As a result of these contextual and mechanistic features, the time taken for the two processes to reach equilibrium can differ (Kärger and Ruthven, 2016).

7.8 Role of mineral constituents

The mineral composition of algal biochar, especially the presence of ash elements, is a determinant of adsorption mechanisms for metalloids. Minerals either electrostatically draw or electrochemically bind charged particles to the biochar surface or take part in complexation. For instance, it was proposed that Sb(III) undergoes outer-sphere complexation with biochar surfaces enriched in ferrous, ferric, aluminic, and silicate minerals. Electrostatic attraction appears to govern the interaction of As with zeolite- and aluminosilicate-rich, non-activated microalgal biochars, while redox transformations facilitate the stronger retention by activated biochars with magnetite content. The affinity of Se for non-activated biochars originating from non-corroded algae is linked to natural organic matter abundance, which is hyper-reduntant in S-, Cu-, Fe-, or Mn-enriched environments. Se(IV) uptake by hybrid adsorbents is largely driven via precipitation with iron-bearing oxides (Tan et al., 2020). The phosphorus content of biochar compounds polymerically stabilises Se, though the dominating pathway remains dependent on the carbonisation operating window. The influence of mineral constituents on adsorption mechanisms with Te and other emerging metalloids requires elucidation. Consideration of ash augmentation with inorganic hydrogels and minerals may also boost As and Sb removal.

The inorganic mineral components of algal biochar can promote the chemical adsorption of metalloids onto biochar surfaces, which accelerates photocatalytic reduction, accomplishes heterogeneous electrochemical reduction, and induces the precipitation of insoluble compounds with significantly lower bioavailability. A possible interpretation of the catalysis of As(III) removal from dyeing wastewater by natural zeolitic biochar is a mechanism that involves the fundamental elements of As and/or probably surfaces, Al–O–P acids capable of catalytic actions. The electrostatic attraction of chlorinated organic compounds to seriously halogen-substituted biochar materials could also be preferentially regulated by the mineral constituents imbedded in the porous structure. These examples suggest that the mineral fractions, together with heteroatom compositions, need thorough analysed to clarify their contribution factors when utilising mineral-mounted biochar for the removal of chlorinated organic pollutants (Rawal et al., 2016).

8 Factors influencing metalloid removal

The influence of specific factors on the metalloid removal of algal biochar-based materials has been examined, with the following observations made. The inherent characteristics of biochar feedstocks play a significant role in determining the sorption performance across various metalloids. The adsorption capacity of algal biochar material was found to generally increase with increasing pyrolysis temperature and was particularly favoured for As(III) at a pyrolysis temperature of 500 °C. Solution pH was identified as a key parameter impacting both the speciation of metalloids and the adsorption process (Kumar et al., 2025). Based on initial concentration conditions, the adsorption efficiency for different metalloids followed a sequence comparable to that of the corresponding distribution coefficients. Increased contact time improved the removal efficiency of As, along with the Kd values for each metalloid species, with 70%–80% removal efficiency for As and Se being achieved within 15 min. For more challenging species, such as Sb, Se, and Te, competitive effects were markedly observed under higher total concentrations.

High initial concentrations resulted in considerable pmT and Te concentration losses upon contact with biochar. However, correlations with removal yield and Kd values suggested that the influence of pH, initial concentration conditions, and concurrently presented ions greatly differed depending on the specific metalloid species. Temperature-dependent studies, complemented by thermodynamic assessment, indicated a chemisorption mechanism for pH-regulated as well as for Se reduction and sorption, while mass transfer limitations were suggested for Te. Natural organic matters either promoted or inhibited pmAs sorption, depending both on the affinity of the natural organic matter component and on the loading position on the algal-derived biochar. Overall, algal biochar has been shown to provide a cost-efficient and eco-friendly material for the removal of various metalloids from the aqueous environment (Pandey et al., 2024).

8.1 Feedstock characteristics

Feedstock characteristics influence the sorption performance of algal biochar. Klemenčič et al. (2019) reported the specific surface area as a critical factor and highlighted biochars from *Nostoc* spp., *Scenedesmus obliquus*, and *Monoraphidium minutum* as particularly effective for Pb, Cu, and Zn removal, respectively. Yang and Zhao noted superior As(III) removal by chitosan-modified *S. obliquus*-

derived biochar, attributed to enhanced surface area and pore volume. A comparative assessment of the biochar characteristics and As(III) and Cu(II) adsorption indicated that surface area plays a more significant role for As(III) than for Cu(II), suggesting varying primary binding mechanisms. Wu et al. emphasised the substantial influence of biochar characteristics on the removal behaviour of different metalloids (Zhao et al., 2022). A comprehensive analysis identified pyrolysis temperature as another key factor, with higher temperatures generally leading to increased adsorption capacity. Tian et al. (2025) established a negative correlation between removal percentage and initial As concentration, consistent with results for various biosorbents.

Preferred pH for metalloid ion removal by biochar is dictated by speciation. The relative concentrations of ions in solution affect removal kinetics and adsorption equilibrium time, with longer times generally favouring biosorbent support. Temperature modulates biosorption mechanisms and affects systems operating at equilibrium. The interaction of biochar and dissolved natural organic matter in synthetic wastewater alters biochar surface properties, the influencing removal performance of Cu(II) and As species (Kołodyńska et al., 2012).

8.2 Pyrolysis temperature

Pyrolysis temperature influences algal biochar adsorption capacity and mechanisms. A rising pyrolysis temperature elevates H and O concentrations, enhances surface smoothness, and introduces porosity. These changes boost iodine and methylene blue number, thus altering dye adsorption kinetics and response to acid and salt. Enhanced porosity increases both dye uptake and intra-particle diffusion.

Higher pyrolysis temperature reduces surface O, shifting from chemisorption to π–π interaction in phenol adsorption. Pb(II) uptake is restricted by diminished H and O and intensified acidic conditions. Zn(II), As(III), and As(V) removal correlates negatively with Zn content and B/Zn ratio. Reduced surface O decreases SO4 = and $H_2AsO_4^-$ removal, while increased π–π interaction positively affects $H_2AsO_4^-$ uptake. Algal biochar pyrolysed above 600 °C is well-suited for removing cationic and metalloids, offering superior removal capacity for Cr(IV) and Cu(II) compared to lower-temperature variants. The anionic species' adsorption is more favourable in alkaline conditions (Li et al., 2026).

8.3 Solution pH

The pH of the solution during removal processes can have several important effects. First, the pH of the solution can control the sorption process by changing the form of the targeted metalloids. For example, as described above, As(III) and As(V) can take different ionic forms at differing solution pH values. The speciation of As is thus pH-dependent, and under different solution conditions, the two forms will exhibit different affinities towards adsorption sites on the biochar surface. Second, the surface of biochar is modified by the pH of the solution, and this can influence the removal capacity for As. The point of zero charge (pHpzc) has been shown to be instrumental in predicting the sorption behaviour of the material. Third, the pH of the solution can also affect competition from accompanying ions, hence altering the removal performance. For example, in the apatite–metabolite system, the substitution of SO_4^{2-} by some anions (e.g. CH_3COO-) at high initial concentration can reduce the removal of As, indicating a membrane-selectivity sequence (Masud et al., 2025).

Reductive As(V) can be transformed into As(III) by Fe(II) present in the solution, and this transformation increases toxicity. Similar pH-dependent behaviour has also been observed during removal by N-doped algal-based carriers. Biochar and various metalloids, their speciation in the solution, and surface charge characteristics are therefore correlated. When pH is lower than pHpzc, the biochar surface is positively charged and metalloids present in a positive state are subjected to electrophoresis towards the negative sites of biochar, thus favouring binding; conversely, at pH > pHpzc, negative sites repel negatively charged metalloids. These interactions are not only limited to As but also apply to Se, Sb, and Te (Shipley et al., 2013).

8.4 Initial metalloid concentration

Metalloid removal efficiency diminishes with rising initial concentration, with the highest occluded mass recorded at elevated levels. pH adjustments affect proportionate pollutant distribution. Biochar–metalloid co-transformation dynamics, including interaction analysis of the composite adsorbent, remain underexplored.

Pollutant uptake by solid-phase adsorbents follows a characteristic profile. Rapid adsorption occurs at low concentrations, with equilibrium approached in a few hours. Large, specific surface area adsorbents retain significant contaminant mass, enabling cost-effective application. Reduction occurs through dilution, thus increasing solution dosage and burden. Contamination degree affects removal efficacy; for instance, Pb on algal biochar decreases from 99% at 1 mg L–1% to 67% at 600 mg L–1 $[NH_4]^+$. Continuous modes retain stable performance, while batch modes exhibit diminishing uptake with rising concentration. Mixed ion systems alter selectivity; for example, combined As(III) and Cl enhance assistive effects but reduce individual removal. Concentration incites configurational activation energy change; high stress-induced ion migration governs thermodynamics (Ahmad et al., 2017).

Algal- and plant-derived biochars differ: plant chars surpass in nitrification potential, Pb retention, and K, Ca, Mg, and SO_4 elution; algal chars excel in N retention, Cr^{+6} reduction, $[NH_4]^+$ and environmental transport-engendered Cl-, Na, and Zn elimination. External approval remains paramount for wood and sludge biochars, while combined systems forge distinct sorption-pathway composites. Algal biochars rival activated carbon, satisfying adsorption quality, cycle limits, and cost, yet maintain reduced coverage capability. Altogether, algal-derived nanomaterials match or exceed standard benchmarks while bolstering accessibility and manufacturing economies (Nguyen et al., 2023).

8.5 Competing ions

Removal efficiency varies with the concentration of solution ions, primarily through competition for the same active sites in bioderived adsorbent materials. Concentrations of other metallic cations exerting significant influence include Na^+, Li^+, Ca^{2+}, Mg^{2+},

Cu^{2+}, Pb^{2+}, and H^{+} ions. Particular ratios favour specific adsorption. However, contaminants at very high concentrations may inhibit removal. When testing metalloids, other ions in solution influence uptake; e.g. phosphate–As interactions affect As–biochar sorption, while higher concentrations of Sb^{3+} depress adsorption of SbV and *vice versa* Chemically activated biochar concentrations also affect metals uptake. The presence of chemical species resulting from industrial effluents affects removal. The presence of NO^{3-} and Cl^{-} promotes the uptake of Pb^{2+}, while these species, when coexistent with SO_4^{2-}, interfere with Ni^{2+} adsorption (Macena et al., 2025).

8.6 Contact time

Contact time does influence sorption capacity but may not control removal efficiency. The duration of sorption often investigated in batch experiments refers to the time elapsed before equilibrium is reached or capacity per unit mass is stabilised. Sorption capacity tends to increase with contact time, reflecting increased probability of diffusion and reactions in sorption systems, until equilibrium is reached. After that point, the amount of adsorbate remains constant, marking the saturation point. Removal efficiency, however, hinges on the nature of the initial concentration. It soars with time when concentrations are low but slows with high concentrations. The increased time for the adsorptive processes leads to an almost constant efficiency per unit mass ratio when initial concentrations are higher than those. Hence, contact time plays an important role in the sorption system equilibrium and helps in determining sorption kinetics, but not in a removal efficiency magnitude (Jain et al., 2020).

For instance, limited contact time (4 h) seems sufficient to achieve >99% removal of 10 mg L–1 As, with expeditious expectations reported for other metalloids—4 h for Te, 5 h for Sb, and only 1 h for Se, reflected in near-zero removal efficiency per unit mass. Removal capacity per unit mass, nevertheless, is normalised by the quantity of metalloid species present in the system.

8.7 Temperature

Temperature effects on sorption capacity and mechanisms have been assessed. An increase in temperature generally enhances the sorption capacity for metals and metalloids, indicating an endothermic process. A notable exception is As, for which removal capacity has been shown to decline with increasing temperature in certain studies, likely due to a reduction in the number of available binding sites. Noticeable changes in electrochemical characteristics during temperature increase are also associated with decreased As-removal capacity. A numerical study into As adsorption from aqueous solutions on an exfoliated KOH-activated biochar derived from *Chlorella pyrenoidosa* indicated an endothermic nature for the process, even across both initial As concentrations investigated. It was proposed that the process was controlled by pore diffusion and chemical reaction (Chakraborty et al., 2022).

Information on the effects of temperature release, particularly in relation to the temperature-dependence of the relative affinity of biochar to different metalloids, is scarce. Studies specifically examining the influence of temperature on the temperature-dependence of sorption capacities of organic and inorganic As forms have not yet been identified in the literature. Temperature-dependence in sorption processes is often investigated as part of a broader thermodynamic analysis of sorption regarding the interpretation of the energetics of the underlying interactions and mechanisms. Interactions between temperature and other common sorption factors for metalloids' initial concentration and solution pH, for example, are also sometimes assessed to establish potentially optimum conditions of removal for a particular bio-adsorbent system. In such cases, the effect of temperature may be indirectly evaluated in conjunction with one or more untested factors (Cipullo et al., 2018).

8.8 Natural organic matter

Interactions between natural organic matter (NOM) and biochar can affect metalloid retention and release. NOM, ubiquitous in soils and aquatic systems, is a complex mixture of organic substances derived from dead plant and animal tissues, microbial residue, and biological activities. It can exist in dissolved form, influencing various soil and water properties. Recent studies have shown that NOM can compete with metalloids for binding sites on biochar, promoting their desorption. Conversely, organic compounds can enhance the retention of certain metalloids, potentially through complex formation with NOM and subsequent binding to biochar.

The influence of NOM on the binding of metalloids depends on its concentration relative to that of the metalloids. At lower concentrations, NOM can promote co-binding, while at higher concentrations it may compete with metalloids for surface binding on biochar. Co-binding may also increase desorption, indicating a weak association of metalloids with biochar surfaces. In acidic conditions, NOM can enhance As(V) sorption and facilitate As-thiol complex formation (Jia et al., 2021).

9 Comparative performance of algal biochar

Reported removal efficiencies for metalloids are often ranked in the order As > Se > Sb > Te and for their mixtures as As > Sb > Te > Se, with arginine-modified ASU biochar showing considerably lower Se uptake. Algal biochars generally outperform plant-derived analogues and H_3PO_4-activated biochar at lower doses, while exhibiting comparable capacities to NaOH-modified biomass, lower costs than nanomaterials, and greater efficiencies combined with KOH activation. Wastewater applications mostly succeed when pollutant concentrations exceed regulatory limits and competitive ion effects are minimal.

Optimising dose selection is crucial; insufficient biochar fails to bind all target species, whereas excessive adsorbent induces rapid deactivation. Natural organic matter in solution can hinder or promote removal depending on the algal feedstock employed. Overall, these materials rank favourably in cost/mass for metalloid removal, enabling compliance with treatment standards for contaminated water resources (Fan et al., 2024). A comparative assessment of the distribution and structural features of Se in aquatic, soil, and sediment systems is shown in Figure 5.

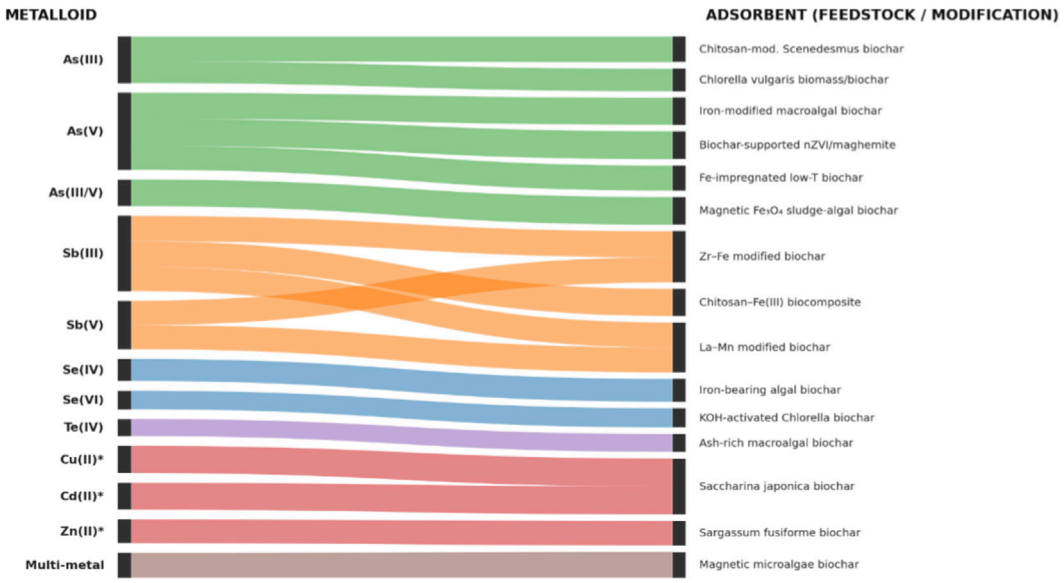


FIGURE 5
Relationship between target metalloids and representative algal biomass- and algal biochar-based adsorbents used for their removal from contaminated water.

9.1 Removal efficiency for different metalloids

Differences in the efficiency of different biochar materials for removing metalloids can be considerable. For example, As, Se, and Sb tend to be removed with higher efficiency than Te and other emerging metalloids, and the mechanisms involved in the removal of different metalloids may differ. These characteristics can be attributed to differences in the nature, composition, and surface properties of the materials used. Such differences may also influence the performance of algal biochar relative to that of other biochar materials. In general, algal biochar exhibits a lower capacity for removing metalloids than biochar derived from wood, leaf, and fruit-shelled plants, while algal biochar displays a higher capacity than glucose-based biochar and a lower capacity than that based on silica. However, among different types of nanomaterials, the capacity of algal biochar for removing metalloids is much higher than that of TiO_2 and CeO_2 nanomaterials, although it is considerably lower than that of a complex Fe-Ce ternary system. Despite the differences in their capacity to remove metalloids, many of these materials do comply with regulations for industrial wastewater discharge (Amabilis-Sosa et al., 2022).

9.2 Comparison with plant-derived biochar

Algal biochar does not always outperform plant-derived biochar on a comparative basis. The differences observed among various types of biochar merit scrutiny, with factors affecting removal efficiencies illuminated in Section 8. Co-removal studies highlight the unique affinities of different biochars, suggesting that a suite of plant-based and algal biochars should be evaluated for specific targets, much as activated carbon types are currently selected for metal removal. Reliance on a single sorbent is therefore unwise, particularly where cost renders some applications and removal targets economically unattainable.

Activated carbon typically delivers superior metalloid removal when loadings are adjusted to take relative capacities into account. Nevertheless, its cost-to-capacity ratio is not as favourable as for less-exploited sorbents. Notably, chemico-thermal activation capability using co-generative gases remains largely unassessed for algal biochar. Direct synthesis of the more effective materials at moderate scale from algal side-streams appears plausible through templating or sacrificial approaches; imperfect replicates can also function. As low-temperature synthesis permits the concurrent removal of toxicity and odour, the cost-to-capacity ratio is naturally heightened (Rammal et al., 2025).

9.3 Comparison with activated carbon

Algal biochar merits comparison with activated carbon for metalloid removal from polluted water and soil. The affinity of algal biochar for metalloids is often lower than that of activated carbon. However, it offers advantages such as lower production costs and abundant availability. The cost expected for the adsorption of metalloids from synthetic waste with algal biochar is 10–120 times that of activated carbon. When used in real effluent treatment, algal biochar can incur a removal cost of less than 0.8 US$ per kg, while figures as low as 0.003 US$ per kg have been cited for some industrial wastewaters. These values reflect feedstock and basic processing assumptions only; they exclude harvesting, dewatering, drying, activation, regeneration, and disposal and should be read as indicative lower bounds rather than delivered treatment costs. The cheaper raw material also permits a lower carbonisation temperature for the preparation of algal biochar. In cases of water-soil remediation, the use of algal biochar can help delay or reduce the cost of activated carbon (Manohara et al., 2021).

The potential of activated carbon modified by other metalloids or contaminants influencing the removal capacity of the adsorbent must be taken into account. Furthermore, research is needed to provide appropriate solutions for treating complicated wastewater using activated carbon. These drawbacks imply that activated carbon should not be the first option for removing metalloids in real wastewater with varied and complex compositions. Rather, finding alternatives is essential in such cases.

9.4 Comparison with nanomaterials

The high removal efficiency achieved by algal biochar with respect to different metalloids is anticipated to make such biochar attractive alternatives to specialised nanomaterials, especially for batch operations. Nevertheless, the low accessibility of nano-agents introduces difficulty in handling them and in supplying them to the receiving substrate in a concentrated form. Consequently, use of nano-agents may often be not feasible for large scale applications, making nanomaterials more attractive for point-based (e.g., as coating agents to targeted sites or species (e.g., fish or plants) or as addition to defined composts prior to their application to soils)) rather than diffuse remediation of aquatic and terrestrial environments. In these cases, an economic cost comparison is needed, since the cost of nanomaterials may, under specific conditions, be lower than using algal biochar, such as for recovering metals from mine drainage, in which algal biochar is presently not very effective.

An economic cost assessment was developed, demonstrating that algal biochar may provide an attractive alternative to activated carbon or other nanomaterials for some remediation applications when the price of such agents is very high due to high recycling costs, additional origin pollution problems, or other variables subsequently listed. However, it should be understood that despite often being more selective than activated carbon, algal biochar usually possesses lower capacities and needs transport to the site of application rather than release along the flow, making natural waters usually not polluted by metalloids and metals unsuitable for their use (Kadimpati et al., 2024).

9.5 Cost-performance analysis

Whether the metalloid is As, Sb, Se, or Te, the distribution and concentration of the respective constituent in the environment affects living organisms. Therefore, for a cost-performance evaluation, the following statement can be generalised: "As natural sorbents for the removal of metalloids from contaminated water, algal biochar demonstrate [*sic.*] lower removal efficiencies than commercial sorbents such as activated carbon. However, the costs of these materials are significantly lower than those of activated carbon, which is also difficult to regenerate, and test results allow for sorption efficiencies to be in a comparable range to those of commercial nanomaterials" (Barik et al., 2025).

Compared to other natural sorbents, such as plant-derived biochar, nanomaterials, and zeolites, the raw materials for producing algal biochar are available at a lower price or, in specific algal blooms or red/green tides, even free of charge. Algal biochar usually presents competitive merits of satisfactory performance with evident resource-recovery efficiencies. Generally, algal biochar presents a cost-related contour of removal efficiency lower than that of activated carbon, comparable to that of commercial nanomaterials, and higher than that of common zeolites (Li et al., 2026). Table 3 summarises these comparisons, listing adsorption capacity, BET surface area, indicative cost and regenerability for algal biochar and for the main competing adsorbent classes.

10 Applications in environmental remediation

Algal biochar can be applied for the environmental remediation of wastewater, surface water, groundwater, and soils. It is particularly effective at removing metalloids, and the treatment of industrial effluents has emerged as an important application. Aside from compliance with regulatory standards, resource recovery in the context of the circular economy remains an attractive prospect (Nguyen et al., 2023).

The treatment of wastewater from various municipal, industrial, and aquaculture sources leads to the removal of pollutants such as phosphorus, nitrogen, sulphides, metals, metalloids, and colour along with a reduction in biological oxygen demand (BOD). The sorption of metalloids like As, Sb, Se, Te, and B can also improve the quality of leachate from landfills. Algal biochar has been proposed for use in constructed wetlands, where it is combined with other media to enhance treatment efficiency. Groundwater remediation has been investigated, with *in situ* applications showing promise for metalloid sorption and immobilisation in a zero-valent Fe-water system. Algal biochar may also support anoxic biochemical denitrification and enhance metabolic activity in permeable reactive barriers. The treatment of effluents from various industrial sources textiles, agriculture, tanneries, agrochemicals, oil refining, and pharmaceuticals has been demonstrated. The simultaneous removal of metalloids such as As and Sb in combination with other pollutants is also possible, thus helping industries meet discharge limits. Resource recovery from metalloids, especially As, in algal biochar systems represents an opportunity that aligns with circular economy aspirations (Deng et al., 2025).

10.1 Wastewater treatment

The application of algal biochar for wastewater treatment has received considerable attention, with promising results for the removal of various contaminants. When utilised as an adsorbent, algal biochar effectively removes colour and effluents from various industrial sectors, such as textiles and tanneries. Phosphates and nitrates have also been removed by different sources of algal biochar. Dyes are among the major contaminants found in aquatic systems, and the application of algal biochar for their removal is gaining momentum, including real industrial wastewater effluents. Se is one toxic metalloid that has been efficiently removed by algal biochar derived from various sources and under different pyrolytic conditions. Huang et al. focused on the removal of As from electroplating industrial wastewater using BCAC. A-SGoB, a residual algal biochar produced from 9-HPAC after removing lignin and holocellulose, can remove Al from neutral solution. Compared to the numerous investigations about As removal

from aqueous solution, however, studies dealing with As treatment from real industrial electroplating wastewater remain scarce (Fernández et al., 2025).

Algal biochar has also shown potential for the treatment of underground water resources. *Bacillus* sp. immobilised and loaded on surfactant-modified algal biochar exhibited the simultaneous removal of pathogenic bacteria and nitrobenzene from underground sources. Algal biochar can also be utilised for on-site remediation of arsenic-contaminated groundwater. Phosphorus-imprinted algal biochar has been used to develop P-hungry, P-sustainable constructed wetlands for controlling the P-risk of construction and demolition waste leachate. Other biochar-based constructed wetlands have also been reported, such as for nitrobenzene treatment. Distinct from the bulk properties of algal biochar produced from green and brown algae wastes, the removal of heavy metals is strongly acid dependent (Verma et al., 2025).

10.2 Groundwater remediation

A wide variety of natural and synthetic compounds contaminate aquifers located above or below the ground. Groundwater sources can be directly treated with specific micropollutants by taking advantage of the porous properties of algal biochar. Wang et al. (2021) used prepared biochar from *Saccharina japonica* in a tubular reactor and achieved high groundwater quality since $[NH_4]^+$, NO_3^-, SO_4^{2-}, Fe^{2+}, Cu^{2+}, Co^{3+}, and Pb^{2+} all decreased to below the detection limits.

Groundwater is the least treated and least monitored environmental matrix, constituting the largest reservoir of liquid fresh water. Due to its extensive use mainly for human consumption, any impairment or lack of quality of this natural resource might severely affect the aquatic ecosystems and human life. In this perspective, the use of biochars for groundwater remediation might be quite promising. Indeed, various treated and untreated groundwaters rich in micropollutants (such as heavy metals, nitrate, pharmaceuticals, and explosives) have been successfully treated during laboratory experiments. Nevertheless, such proof-of-concept studies should evolve to higher technology readiness levels, and approaches to evaluate potential scaling and decommissioning should be integrated (Foster et al., 2013).

10.3 Soil remediation

In both terrestrial and aquatic environments, metalloids can leach into the soil or sediment, posing a threat to crops or ground- and surface-water quality. Algal biochar has been studied for use in contaminated soils and in terrestrial environments that can act as release sources for pollution through surface run-off, thus further threatening the water bodies. Adding biochar to contaminated soil can lower the bioavailability of metals and metalloids and reduce their uptake into plants. It may also improve plant performance by supplying macro- and micronutrients, correcting mineral deficiency, and increasing fertiliser-use efficiency (Qadir et al., 2024). Comparable co-benefits have been reported for algal biochar (Zhao et al., 2022; Nigam et al., 2020), although most of this evidence comes from short-term pot trials rather than field application, and the safe disposal of metalloid-laden biochar has not been demonstrated at scale.

Algal biochar can effectively immobilise metals (e.g., lead, copper, and chromium) and metalloids (primarily As) in soil and play a significant role in its restoration. All the pollutants are efficiently immobilised by the biomaterial in a single nano-adsorption process. Algal biochar can help alleviate As uptake by rice roots and reduce its translocation to shoots and grains; it is also reported to have a positive synergistic effect on plant growth and fertiliser application. The Fe-, Ca-, and Mg-enriched algal biochars derived from culturing *Chlamydomonas* sp. and *Spirogyra* sp. species can effectively decrease As concentration in the edible parts of rice. An integrated treatment has been claimed to be a successful way of removing or minimizing heavy metals/metalloids from the aquatic system and use algal biochar-saturated soils for healthy crop production in soil (Kumar et al., 2025).

10.4 Constructed wetlands

Constructed wetlands offer a novel venue for integrating algal biochar into metalloid removal systems. Algal biochar can efficiently operate as a filter or sorbent in either vertical- or horizontal-flow configured substrates, including solutions diluted in wastewater fungal leachate and trapezoidal water channels infused with low concentrations of zebrafish wastewater susceptible to contamination. Major removal mechanisms involve anion exchange and physical adsorption, the priority of which varies with biochar pyrolysis temperature. Moreover, abiotic and biotic activities mobilise the adsorbed metalloids, releasing natural resources from surface complexes into the water for recycling. Given their benignity and notable exchangeability, algal biochar-assisted wetlands have the potential to upcycle and remediate contaminated water in the circular economy (Singh et al., 2025).

Long-term success requires stability and favourable aging conditions of the biochar used; secondary pollution during use and ecotoxicological risks for non-target organisms such as bacteria, algae, fauna, fish, and crops should be avoided. Afterwards, users must consider its safe disposal, potential regeneration through low-energy recovery methods, and end-of-life management pathways with limited environmental impacts. As these aspects enter consideration, a connection might gradually emerge with advanced management schemes such as life cycle assessment and responsible research and innovation strategies. When adhering to appropriate conditions, algal biochar can indicate a generally acceptable use in bioresources and applications in the larger framework of environmental policy (Fernández et al., 2025).

10.5 Industrial effluent treatment

The unique physiochemical characteristics of algal biochar correspond to superior adsorption affinities for certain ions, making it a highly regarded material in environmental restoration efforts. Generating biochar with targeted adsorption properties provides a functional solution for many wastewater-pollution scenarios while also minimising potential pathological damage within industrial ecosystems and meeting regulatory removal thresholds for emerging environmental contaminants. The construction of an algal biochar–metalloid nexus establishes the foundations for the proper selection and engineering of algal

biochar that can effectively reduce specific metalloids within polluted wastewater (Tan et al., 2023).

Industrial processes can produce large quantities of metalloids, leading to environmental endangerment if these effluents are discharged without treatment. Furthermore, persistent metalloids within various environmental compartments can eventually enter human food chains. In addition to direct human toxicity, metalloids such as Se and Te can also adversely affect non-target fauna and flora, causing greater destabilisation of the ecosystem. Using algae as green ameliorating agents to facilitate the treatment of industrial wastewater offers a dual benefit, reducing algal-bloom biomass while remediating metalloids generated by industrial activity (Barik et al., 2025).

10.6 Resource recovery

Algal biochar development for metalloid removal has largely focused on adsorption efficiency rather than considering resource recovery. Nevertheless, metalloid-laden algal biochar can be used to recover valuable nutrients, including nitrogen, phosphorus, and potassium, which can promote plant growth if reintroduced into the soil. Metalloid-rich algal biochar has been applied as fertiliser in crops such as rice, millet, mustard, and wheat, resulting in increased yields compared to control conditions. Algal biochar enriched with biochar-derived nutrients has also facilitated plant growth. Consequently, plants cultivated on metalloid-laden algal biochar have stabilised metalloid content in untreated soils (Gan et al., 2018). Other studies have illustrated the capacity of As- and Se-laden algal biochar to sustain plant growth, establishing feasible outlet options for As pollution. Moreover, integrating algal biochar with natural zeolite can enhance cost-to-benefit ratios during subsequent use. A systematic evaluation of N and P release from algal biochar has underscored the influence of pyrolysis conditions. Depending on the intended use, the relative amounts of water-soluble N and P in algal biochar can also be manipulated through hydrothermal carbonisation temperature optimisation. Because K and P solubility generally increases during ageing, Se-laden algal biochar has been proposed as a potential potassium source (Shang et al., 2025). This remains an open research question rather than a recommendation: the land application of metalloid-laden biochar would require leaching, ecotoxicity, and regulatory data that are not yet available.

However, nutrient recovery from metalloid-laden algal biochar constitutes an emerging area of investigation, and adequate guidance is presently lacking. Similarly, ongoing work is needed to identify and reduce potential negative impacts associated with resource recovery through biochar application on soil systems or direct plant cultivation experiments.

11 Waste valorisation and circular bioeconomy

Algal biochar could serve as a key metalloid-remediation agent that furthers circular bioeconomy goals, provided that algal waste valorisation pathways are carefully designed. Biochar produced from algal biomass or algal waste valorisation pathways enables dual benefits: the mitigation of pollutant presence in the environment and the return of nutrients back to the soil, thus closing the nutrient cycle. Life-cycle analysis results suggest that, when taking only the recalcitrance of climatic change and carbon sequestration potential into account, the application of algal biochar in the soil should be promoted. Integrating nutrient-reutilisation strategies, such as the application of biochar in agricultural land, for growing algae as biomass feedstock would not only reduce environmental pollution resulting from nutrient discharge but could also improve the economy and carbon-neutral development. The highly brittle nature of algae-derived algal biochar/constructed wetland could facilitate the feasible and effective treatment of industrial wastewater to meet discharge standards and also recover metal resources in industrial wastewater (El-Naggar et al., 2022).

Biochar production from algal feedstocks could also support the circular bioeconomy model if properly designed, and opportunities for combined bioenergy production with the biochar-mediated removal of organic pollutants and metalloids from wastewater should be investigated to achieve better economic performance. Life-cycle analysis of an *A. platensis* biochar utilisation system, considering potential C sequestration and nutrient recycling, suggests that, regardless of the waste treatment pathway, such biochar should be applied to the soil. The application of nutrient-rich residues from wastewater treatment or food-processing wastewater should be strongly recommended, alongside the exploration of other additional algal biochar quality comparisons, such as cost versus adsorption capacity, to achieve safe and effective treatment of either source-water or industrial pollutants (Claret et al., 2025).

11.1 Algal waste utilisation

Waste algal biomass has attracted considerable interest as a feedstock biofuel production (propagating carbon-neutral energy), biomolecules (biofuels, biofertilisers, biopolymers, biosurfactants, etc.), and biochar (for metal/metalloid removal, soil rejuvenation, etc.). Growing interest in biogas production from non-degradable microalgal biomass has prompted a consideration of the selective anaerobic digestion of algal residuals for producing biochar. Algal biochars have thus been mainly investigated for their short-range structural features (morphology, surface area, porosity, inorganic composition, surface electronegativity) and their affinities for As, Sb, Se, Te, and other emerging metalloids. The removal of As, Sb, and Se from various environmental media (contaminated wastewater, groundwater, surface water, soil, sediments) using algal biochar has received particular attention, with a recognition of the key impact of precipitation/co-precipitation processes involving inorganic constituents. These hybrid roles suggest that algal biomass valorisation routes that target end-of-life algal waste also need to consider biochar properties and the ability of biochar to draw down hazardous metalloids from contaminated environments (Mehmood et al., 2024; Kumari et al., 2023).

The dumping of algal waste into landfill causes severe environmental pollution, highlighting the urgent need for the valuable utilisation of algal biomass that is not suitable for high-value biofuel/bioactive compound production. A circular economy approach should therefore support the development of integrated systems to produce valuable biocarbon and other biochar-rich

organic materials capable of immobilising toxic/metalloid pollutants. Natural gas production from the anaerobic digestion of non-biodegradable microalgal biofuels is a further potential resource along the integrated route. As pollution and resource depletion crises intensify, algal biomass needs to be converted into useful resources that support environmental sustainability (Pal and Mahmood, 2026).

11.2 Carbon sequestration potential

Potential for carbon sequestration in algal biochar systems has received limited attention, with only one study highlighting the long-term storage capacity of aged intake. Aging tests, conducted over 3 years in paddy soil, have indicated a modest accumulation of *C*-coated iron oxides and *C*-enriched clay minerals, alongside diminished signs of biochar degradation. Resilient microalgae-derived organic matter–metal oxide complexes appeared to stabilise biochar for extended periods, suggesting resistance to microbial degradation. Notably, treatments containing marine microalgal biochar exhibited the highest level of *C*-sequestered benefits. The evaluation of mineral soil, however, reveals a lack of evidence to support biochar's long-term *C* stabilisation capability. Addressing this gap should be prioritised in future studies (Hoque et al., 2025).

A bioenergy–biochar coupled system offers a synergistic approach for harnessing renewable energy while simultaneously mitigating waste issues. Spent microalgal biomass presents a promising feedstock for biochar production through either pyrolysis or hydrothermal carbonisation, with the possibility of the subsequent incorporation of nutrients and heavy metals for enhanced compatibility in soil and water systems. Combinations with metal- (metallic/metallic oxide) infused algae also show potential for energy recovery along with the nutrification of carbonised products. Moreover, activated biochar can efficiently remove residual soluble nutrients from wastewater, thereby enhancing the efficiency of water-sediment-reservoir systems. The approach provides a mechanism for the continuous removal of non-helical soluble nutrients and heavy metals from the water–sediment body (Fryda et al., 2018).

11.3 Bioenergy integration

The simultaneous production of bioenergy and biochar has been explored in order to lower overall operation costs of algal waste valorisation. Hydrothermal treatment using hot compressed water to extract bio-oil while producing biochar from the residual algal cake reduced energy demands by 62% and processing costs by 33% compared with single-product scenarios. However, keeping biochar production temperature below the optimal range diminished bioenergy potential but capped CO_2 emissions and retained critical nutrients. Biochar-assisted algal anaerobic digestion was reported to enhance biogas generation by 22%–40% and reduce heavy metal concentrations in the digestate. Converting residual algal biomass to biochar-rich soil amendments via gasification improved nutrient profiles and reduced heavy metal concentrations. Bio-habitats constructed from treated algal mud also supported enhanced anaerobic digestion and algal growth (Brindhadevi et al., 2021).

Algal-biochar-assisted pyrolysis has produced dual-product biochar and bio-oil, with the latter resistant to heavy metal contaminants in the source algal sludge. The co-pyrolysis of *Mesocyclops mejanus* with separated municipal sludge has aided wastewater management via heavy metal reduction, energy recovery, and biochar generation. The integration of algal biomass and swine manure in anaerobic co-digestion enhances energy recovery and accelerated carbon recycling through spontaneous vegetation growth. Positive algal-microflora relationships in treated piggery waters have supported rapid plant growth in biosafety tests at varying algae–water ratios, with bioenergy recovery projected from subsequently generated biomass (Yu et al., 2017). Toxicity mitigation in microscopic studies has also been reported during the rapid phytoremediation of dairy effluents treated with algae.

11.4 Nutrient recycling

The application of algal biochar in soil provides a suitable nutrient source for plant growth. Biomass yield is enhanced when algal biochar is blended with chemical fertilisers. In contrast, soil application of algal biomass, charcoal, or slurry is not suitable for crop production due to N immobilisation. Biochar adsorbs metals, preventing their leaching from treated soil. Its addition to metal-contaminated soils enhances plant growth and decreases the accumulation of toxic metals in plants. Biochar fulfils the metal and sulphur requirements of plants (Abideen et al., 2022).

The application of algal biochar decreases soil pH, enhances electrical conductivity, and increases bioavailable nutrients. Therefore, its application can be combined with chemical fertilisers to enhance the biomass yield of crops. The permissible application rate of algal biomass may be determined through basil or tomato cultivation trials. Biochar is chemically stable and, with mineral addition, can recycle nutrients such as N, P, and K in soil, slowing their leaching and increasing plant uptake. The application of nitrogen-containing biochar can also shorten fertiliser-burning periods in the dry season.

In anaerobic co-digestion systems, biochar from other cultures release ammonium and phosphorous and can be used as slow-release fertilisers. Biochar from anaerobic digestion or fermentation having high C–N ratios compared to algal and chemical manure requires long-term organic fertiliser reduction to enhance soil organic carbon concentrations. However, due to the long-range transport of nitrate nitrogen in soil, using algal biochar alone is not suitable for crop production; its application requires a large quantity of N fertiliser and can serve only as a N-efficient agent (Jacob et al., 2025).

11.5 Life cycle sustainability

Valuable insights into life cycle sustainability and environmental effects are essential to ensure that the use of algal biochar for metalloid removal does not give rise to more serious or harmful consequences elsewhere. Such an assessment should include: quantification of the carbon pool and its persistence in biochar; possible adverse consequences of the biochar's leachates at different concentrations on the surrounding environment; the occlusion or release of metalloids with associated toxicity as a result of the aging

process; the uptake and accumulation of the treated metalloids by animals in the food chain; possible harmful effects of adding algal biochar to the environment on ecological organisms, including non-target aquatic or terrestrial flora and fauna, as well as humans (Shang et al., 2025); the type of risk imposed (ecotoxicological, exposure, hazard, or other) and the strategy employed in assessment, such as probabilistic, logical-qualitative, or qualitative feature-based; the nature of the environment into which it is discharged (soil, water, or air); the biological or ecological target considered; the attributes being tested (toxicity, persistence, bioaccumulation, etc.); the action pathway for risk description (leaching, sorption, transformation, etc.). The experimental set-up must consider the regulatory specifications for the treatment of the examined sample (water, sediment, etc.) in order to verify that the water quality standards for the treated metalloids are being met. Most importantly, risk management measures must be identified to ensure that any secondary contamination problem occurring during biochar use is minimised or that a remediation strategy for natural saline water and soil is considered (Ndirangu et al., 2019).

Several biochars produced from algal waste may contain excessive levels of toxic elements/metalloids and pose an environmental hazard upon application to the land. Safe disposal guidelines must therefore be developed based on a combination of standards adopted at different geographical scales and toxicity test assays. During disposal and potential re-adsorption in negative environmental settings, metalloids may nevertheless be transformed into less toxic, more environmentally friendly forms. Thus, in addition to biochar synthesis, attention must be paid throughout its life cycle and at final disposal. Life-cycle impact assessment and decision-support methodologies should additionally be applied for selecting optimal pathways when more than one biochar using different feedstocks or synthesis methods is available (Kumar et al., 2022).

12 Environmental and ecological risk assessment

Evaluating the potential risks and repercussions of using algal biochar during remediation and in environmental media is vital to ensure safe application. Investigating the stability and aging processes of algal biochar during its use and after deposition in the environment is critical. The leaching of metalloid species, nutrients, or additional contaminants from the biochar into the surrounding media can induce secondary pollution. The ecotoxicological impacts of algal biochar on non-target organisms such as bacteria, plants, shrimp, and fish should also be assessed to determine safe application rates. Consideration of the material's fate after use can improve sustainability: the development of regeneration methods, management practices for safe disposal, and evaluation of end-of-life options are necessary (Huang et al., 2025).

When properly managed, the algal biochar–metalloid nexus is a promising solution. Its use can result in the remediation of natural and engineered systems polluted by metalloids while contributing to relevant objectives of the circular bioeconomy. Preliminary life-cycle analyses indicate that algal biochar can deliver both environmental benefits and resource gains; nevertheless, further refinements remain necessary. Continued support is essential to overcome the remaining challenges and risks associated with generation and use. Regulatory guidelines that specify safe use, any required pre-treatment, and justification for application rates should facilitate wider use in a variety of contexts (Jiang et al., 2021).

12.1 Stability and ageing of algal biochar

Dominant abiotic processes that influence biochar components and structure (e.g., oxidation, leaching, lateral diffusion of soluble entities within biochar pores) over extended periods must not compromise algal biochar usefulness and performance. Most research findings are encouraging, with algal biochar showing reasonable stability during environmental exposure. However, reduced functional group concentrations or alterations in their electronegative charge after ageing diminish positive surface interactions with anionic substances. Biochar oxidation, driven by molecular oxygen or chemohydrotrophic bacteria, also diminishes sorption capability for several potential contaminants. The formation of oxidised organic compounds results in leaching of cation-exchangeable ions (e.g., Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+}) that are necessary nutrients. Even the very small population of biosphere-resident yeasts, for example, can break down functional groups of biochar (Murtaza et al., 2023).

Algal biochar is promising for various new applications, including the removal of anions from several aqueous matrices, as well as for possible future use as phosphorus fertiliser. However, further studies on the ecotoxicological risk of aged, leached biochar applied to the soil–plant system are suggested, especially if natural organic matter-rich leachates are utilised for irrigation purposes. Research on other meta-ingredients, loadings of other compounds, and ageing time is required for other meta-elements. In addition, the growing body of evidence on the beneficial or detrimental effects of biochar on non-target organisms in surface waters must also be considered (Pahlavan et al., 2024).

12.2 Secondary pollution risks

Secondary pollution may arise from leachates during biochar application, thus compromising the environment and human health. Laboratory studies have shown that sorption generally decreases with increasing pH, suggesting the possibility of leachate toxicity from dissolved metalloids. The clay component in biochar may also dissolve under alkaline conditions, affecting the interactions between the dissolved metalloids and the leachates and eliciting toxicity even in low concentrations. Laboratory leaching experiments can indicate potential secondary pollution from biochar. Investigating biochar composition may provide insight into the metalloids likely to be leached (Hasnain et al., 2026).

Factors such as pyrolysis conditions and the abundance of nutrients can simultaneously sustain healthy plant growth and enable the incorporation of excessive metalloids and nutrients into biochar without inducing leaching or secondary pollution. Natural aging can also minimise leaching problems, as shown by a decrease in the leaching potential of Zn from pyrolysed *Spirulina platensis* biomass after 90 days of weathering. In addition to leaching, the leachates can also introduce potential pollution risks. For example, although Si in biochar is an essential

nutrient, excessive quantities exceeding the suitable Si content for plant growth may be bioavailable in the leachates, which may adversely affect the growth and health of both terrestrial and aquatic organisms.

However, leachate studies on the potential release of metalloids, heavy metals, and nutrients from biochars prepared from different feedstocks at varying pyrolysis temperatures remain limited, and more in-depth investigations are required to elucidate secondary pollution risks from leachates. Ecotoxicological impacts on non-target organisms, including mint seeds, earthworms, and daphnids, have been evaluated, with toxicity closely related to the concentration of leachate-extractable heavy metals in both biochar and other forms of biomass. It is notable that exposure to leachates derived from biochar produced at low temperatures exhibits higher toxicity than exposure to extractant leachates. Moreover, while NH^{4+}-N is beneficial for plant growth, excessive NH^{4+}-N in leachates can lead to subsequent secondary pollution risks (Zhang et al., 2021).

12.3 Ecotoxicological impacts

Concerns regarding the ecotoxicological effects of algal biochar on organisms other than those of prime interest have started to receive attention, given the considerable breadth of non-target organisms in the ecosystem. Algal biochar derived from engineering approaches such as sulphur addition is also showing considerable shifts in biochar's properties—hence its ecotoxicological behaviour. However, many of these ecotoxicological investigations remain largely limited to bacteria and *Daphnia* species. In addition to these organisms, groups such as insects, fungi, amphibians, earthworms, fish, crustaceans, algae, and plant seedlings should not be overlooked in evaluating the loss of ecosystem functions and services, as well as possible effects in the early stages of the food chain (Inaudi et al., 2025).

Biochar pollution may not necessarily lead to adverse ecological consequences for the earthworm species *Aporrectodea caliginosa*, at least during exposure in the culture medium. By comparison, ecotoxicity tests using the test organism *Daphnia magna* may still precisely demonstrate the ecotoxicity of algal biochar produced with high pyrolysis temperature in relation to acid-activated carbon by BAM (Germany) accreditors. These responses indicate that a combination of corn straw and activated sludge-derived biochar synthesised at different pyrolysis temperatures and/or conditions cannot be considered toxic based solely on the absence of toxic effects on *D. magna*. The toxicity of biochar in general needs further assessment and correlation with concentrations or quality changes caused by biochar interacting with the growth media of living organisms (Murtaza et al., 2022).

12.4 Safe disposal and regeneration

Assessments of biochar safety and environmental performance have so far neglected the potential risks associated with unloading algal biochar into aqueous ecosystems (surface water, groundwater, and sediment) and terrestrial systems (soil, actual plants, and runoff water). Thus, the likely toxicity of washed-used algal biochar and the toxicity of fresh algal biochar for non-target organisms should be studied. Furthermore, minimising/mitigating these secondary pollution risks can help steer the broad acceptance of algal biochar in commercial applications and product developments. The life cycle of algal biochar in real-world environmental systems is still poorly understood and warrants examination. After its application, whether in aquatic systems or soil systems, the long-term evolution of the biochar in the targeted environment should be monitored. Notable alterations in its properties after prolonged aging (e.g., substantial loss of C, S, surface area, functional groups, and hydrophobicity) suggest that biochar becomes increasingly unstable and may thus exert a weakened capacity to retain metalloids or other contaminants (Huang et al., 2025).

In such a scenario, regeneration becomes pertinent. Follow-up treatments of used biochar (thermal and chemical) should also be explored, as should the performance of regenerated biochar in the removal of toxic metalloids. Furthermore, the inherent toxicity of algal biomass to different organisms must be documented. Such knowledge is crucial to address public concerns surrounding the application, through dispersion, or direct utilisation of algal biomass in natural systems. The above lines of research will provide further insights into both the biosafety of fresh algal biochar for non-target organisms and the potential for regeneration of used algal biochar. Moreover, life cycle considerations that incorporate both aspects are essential for underpinning regulatory policies and commercialisation efforts in the resource recovery domain (Portmann et al., 2022).

12.5 Regulatory considerations

Given the diverse applications of algal biochar, regulatory oversight by national authorities is essential to ensure product quality and safety. Region-specific guidelines for algal biochar have yet to be established, so products are often classified according to those for plant-based biochar. Emerging research suggests that algal biochar may pose specific risks associated with metalloid leaching, organic contaminants, or elevated nutrient concentrations, thus requiring careful evaluation of potential impacts on both environmental and human health (Hammond et al., 2016).

To ensure safe use, algal biochar must be subject to ecotoxicological tests and effect predictions based on quantitative structure–activity relationships (QSARs). Such assessments will help establish ecologically relevant application rates and identify permissible limits for the leaching of potentially harmful compounds. Control of these leachates can include placement of the amendment away from drainage systems and buffering against pH changes to diminish the risk of soluble metalloids. Procedures for end-of-life management should also be articulated, either through biodegradation or regeneration of biochar activity via heat or chemical treatments, incorporating microbial–algal–plant consortia to facilitate these processes (Dudek et al., 2006).

13 Conclusion

Metalloid pollution remains a persistent risk to human health and to ecosystems, and the strategies available to manage it are still limited. Algal biomass constitutes a renewable, sustainable feedstock for biochar production, capable of supporting circular economy and

bioeconomy objectives. Algal biochar shows clear promise for metalloid removal from contaminated water and soil. The evidence supporting safe field use, however, remains thin: most data derive from laboratory batch tests on synthetic single-metalloid solutions, and leaching, ecotoxicity, and end-of-life data for spent, metalloid-laden biochar are largely absent. Nevertheless, further investigations are required to address critical knowledge gaps, validate current results, and promote real-world applications. Continuous efforts are also essential to explore novel valorisation pathways for degraded or wasted algal biomass in order to provide effective solutions for bioenergy recovery, metalloid remediation, and environmental sustainability. Metalloid distribution and transport in aquatic, soil, and sediment systems demand ongoing monitoring, modelling, and predictive assessments in conjunction with the development of remedial technologies capable of reducing risks associated with their presence. Safe and efficient algal biochar utilisation for the removal or immobilisation of contaminant metalloids could facilitate wastewater treatment, drinking-water supply, aquifer protection, soil quality enhancement, ecosystem improvement, and the production of metalloid-free food. Simultaneously, these approaches would support the goals of waste valorisation, resource recovery, and circular economy. Further studies should address the aging and transformation of algal biochar in natural environments, evaluate the consequent effects on its metalloid-binding capacity, and monitor possible side effects on non-target organisms during and after remediation. Four priorities follow from this review. First, column and pilot-scale testing in real water and soil matrices is needed in place of further single-metalloid batch isotherms. Second, pyrolysis conditions, sorbent dose, pH, initial concentration, and matrix composition should be reported in a standardised form so that capacities can become comparable across studies. Third, binding mechanisms should be confirmed spectroscopically—for example, by XPS or XANES—rather than inferred from isotherm and kinetic model fits alone. Finally, leaching, ecotoxicity, and disposal data for spent biochar are required before the land application of metalloid-laden material can be considered. The evidence base is currently strongest for arsenic, moderate for selenium, and insufficient for antimony and tellurium, and this imbalance should shape the next phase of research.

Author contributions

VS: Methodology, Formal Analysis, Data curation, Writing – original draft, Resources. RS: Software, Writing – original draft. MS: Methodology, Investigation, Supervision, Writing – review and editing. KA: Formal Analysis, Validation, Supervision, Writing – review and editing, Methodology, Conceptualization. RM: Writing – review and editing, Software. YK: Writing – original draft. RG: Resources, Writing – review and editing, Software. GA: Project administration, Validation, Visualization, Conceptualization, Supervision, Writing – review and editing.

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Supplementary material

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