Review

Advances in Functionalized Bacterial Cellulose Composites for Heavy Metal Adsorption: Mechanisms, Regeneration, and Scale-Up Prospects

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Advances in Functionalized Bacterial Cellulose Composites for Heavy Metal Adsorption: Mechanisms, Regeneration, and Scale-Up Prospects

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Abstract

Contamination of water with heavy metals remains a life-threatening global concern due to the persistence, toxicity, and bioaccumulation of metals such as Pb(II), Cd(II), Cu(II), and Hg(II). Conventional remediation technologies, including ion exchange, membrane filtration, and precipitation, offer limited scalability and often generate secondary waste. In contrast, bacterial cellulose (BC) and its composite derivatives have emerged as sustainable bioadsorbents with tunable surface chemistry, high porosity, and exceptional biocompatibility. Over the past decade, BC-based materials have achieved adsorption capacities up to 571 mg/g for Pb^{2+}, 509 mg/g or Cu^{2+}, and 382 mg/g for Cd^{2+}, outperforming most traditional bioadsorbents. This review systematically analyses the structural design, surface functionalization, and mechanistic pathways governing metal ion capture by BC composites. Special emphasis is placed on correlating modification strategies (carboxymethylation, amination, magnetic) with adsorption kinetics, thermodynamics, and regeneration efficiency. Compared to previous reviews, this work uniquely integrates quantitative analysis, multi-metal adsorption behaviour, and insights from real wastewater applications, highlighting critical gaps in scalability, durability, and regulatory readiness. Finally, we outline future research trajectories, including green synthesis optimization and integration with hybrid technologies (photocatalysis and electro-adsorption) to link the gap between performance of research laboratories and industrial deployment. By providing a mechanistically grounded and application-oriented perspective, this review positions BC composites as next-generation materials for sustainable heavy metal remediation.

Keywords: bacterial cellulose composites; remediation; water purification; sustainable materials; reusability

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1. Introduction

Water pollution from rapid industrialization remains a global challenge, with heavy metals representing a particularly critical threat due to their persistence, non-biodegradability, and toxicity to ecosystems and human health. Major sources include industrial and agricultural goings-on, pharmaceuticals, domestic runoffs, and atmospheric deposition [1]. Toxic ions such as Cd(II), Hg(II), Pb(II), Cu(II), As(III), Cr(VI/III), and Ni(II) readily enter the food chain, bioaccumulating at the highest trophic levels and causing serious health diseases as mentioned in Table 1. Protecting water and food resources from such contamination is therefore an urgent priority [2].

Growing interest in removing and recovering toxic as well as precious metals from water stems from both environmental and resource considerations, with several classifications of raw materials being critical under the Materials Initiative [3]. Existing technologies, including membrane filtration, chemical precipitation, ion exchange process, electrochemical method, and photocatalyst, offer solutions but are often costly or limited in scalability [4–10]. Among them, adsorption stands out as an efficient and economical approach, valued for its simplicity, versatility, and broad applicability to organic and inorganic pollutants [11,12]. The effectiveness of this process, however, depends strongly on the choice of adsorbent, which must balance stability, capacity, porosity, cost, and biodegradability in line with industrial and environmental policy demands [13,14].

Table 1. Heavy metals toxic effect on human beings' health [15–18].

Heavy metals	Toxicity effects
Copper	diarrhoea, allergic reactions, nausea, vomiting, and damage to the kidneys and liver.
Cadmium	kidney damage, cancer, deterioration of bone health, cardiovascular consequences, respiratory problems, birth defects and infertility, cognitive decline, and gastric impacts.
Lead	cognitive decline, impulsivity, anemia, hypertension, kidney damage, neurological disorders, digestive disorders, and trouble absorbing nutrients.
Chromium	Lung cancer, skin allergies, respiratory problems, kidney and liver damage, DNA damage, and genetic abnormalities.
Nickel	Damage to the kidneys, liver, and lungs; the emergence of long-term respiratory disorders; allergic reactions and skin hypersensitivity.
Cobalt and Mercury	polycythemia, peripheral neuropathy, and cognitive impairment. effects on the nervous system, kidney damage, problems with the gastrointestinal tract, respiratory system, heart, reproductive system, immune system, and skin.

Conventional inorganic adsorbents such as activated alumina, iron oxides, activated carbon, and nanomaterials face drawbacks as well as high cost, complex preparation, and poor biocompatibility [19]. This has accelerated the search for sustainable alternatives that are biodegradable, low-cost, and environmentally friendly [20]. Bioadsorbents derived from renewable biomass have emerged as promising candidates, offering a viable and eco-efficient route for removing toxic metals from water and wastewater [21–23] (Figure 1).

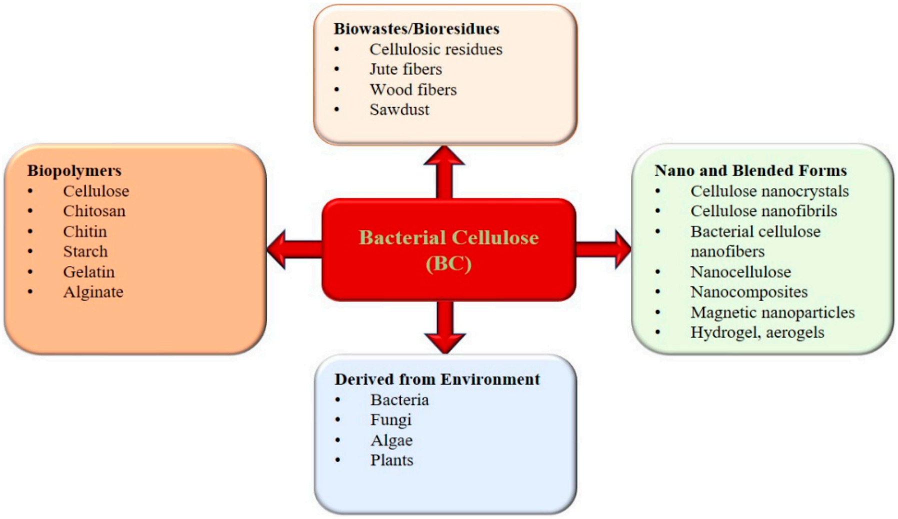

Figure 1. Bacterial Cellulose (BC) vs various bioadsorbents stated in the literature [24].

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Polysaccharides, as renewable and biodegradable biopolymers, can adsorb diverse contaminants via chemical and physical interactions, offering an inexpensive strategy for aquatic decontamination [25]. Among them, cellulose is abundant, non-toxic, and biocompatible, with numerous hydroxyl groups that enable functional modifications and enhance the adsorption of aqueous contaminants [26]. Due to their potential of metal ions adsorption, materials based on cellulose-composite materials have drawn a lot of interest from scientists; in fact, they have been studied since the 1990s [27]. Beyond plant sources, certain bacteria, including *Gluconacetobacter*, *Acetobacter*, and *Pseudomonas*, produce bacterial cellulose (BC), which shares the molecular structure of plant cellulose but forms an ultrafine nanofibrous network [28]. BC can be produced via static fermentation, yielding membranes, or agitated fermentation, generating spherical forms having nanopores and large surface area and, suitable for heavy metal removal and bio-separation [29,30]. Efficient strategies to synthesize high-performance cellulose-based bioadsorbents remain critical.

In this review's Section 2 briefly explain an overview for adsorbent of cellulose. Next part we will 3 evaluates their classification into three major types: (i) surface functionalized cellulose materials, (ii) blended cellulose materials, and (iii) cellulosic biomaterials. The metal ions evaluation as adsorbent divide into three major parts : (a) ions of PTEs such as Ni(II), Cu(II), Cr(III), Cr(VI), Hg(II), Cd (II), Zn(II), Pb(II), Co(II), Fe(III), As(III), and As(V); (b) ions of RNs such as U(VI), 137Cs(I), 90Sr(II), 60Co(II), 140La(III); and (c) ions of PMs such as Au(III), Ag(I), Pt(IV), and Pd(II). At the end, Section 4 give overview of upcoming trends of cellulose-based adsorbents, while Section 5 discusses challenges and future perspectives.

Bacterial Cellulose (BC) is a promising bioadsorbent for heavy metal removal due to its three-dimensional nanofibrous network, high surface area, porosity, abundant hydroxyl groups, and water-holding capacity [31,32]. However, its limited adsorption capacity, selectivity, and stability under variable conditions restrict practical applications. Composite strategies, incorporating bioactive polymers, nanomaterials, or solid particles, have enhanced BC's adsorption efficiency and added functionalities such as antimicrobial, conductive, and magnetic properties [33]. Recent research emphasizes developing cost-effective and environmentally friendly BC derivatives for water treatment. This review systematically summarizes BC-based adsorbents, including surface-functionalized cellulose, blended composites, and cellulosic biomaterials, and evaluates their mechanisms and effectiveness for removing diverse metal ions, including potentially toxic elements, radionuclides, and precious metals, while highlighting current trends and future perspectives.

- Design s multifunctional materials for water treatment is still remains a challenge.
- Recently a major challenge is to design derivative BC composite related to economical and environmentally friendly problems.

Mainly this review offers a comprehensive outline of bacterial cellulose (BC) and its composite-based adsorbents as sustainable, cost-effective, and high-performance materials for the elimination and recovery of toxic and valuable metal ions from contaminated water. By examining the structural features, functionalization strategies, and adsorption mechanisms of BC-based systems, this review aims to highlight their potential in addressing both environmental remediation challenges and resource recovery needs. We hope this review will encourage more researchers to design and implement innovative bioadsorbents based on BC, advancing sustainable strategies for water purification and resource recovery.

2. BC Synthesis and Properties

BC produced by Gram-negative bacteria such as *Acetobacter* and *Gluconacetobacter*, is synthesized from carbon-rich media, with Hestrin-Schramm (HS) medium widely used [34]. Source to produce the BC by using static, agitated, and bioreactor cultures, affect its morphology and mechanical properties. Static cultures yield strong membranes but face oxygen limitations, agitated cultures improve nutrient supply at the cost of mechanical strength, and bioreactors enhance scalability but introduce shear stress and higher energy demands [35–45]. Method selection depends on the intended application.

BC contains hydroxyl, amino, carboxyl functional groups that facilitate binding with heavy metal ions [46]. Structurally, cellulose is a linear polymer of β-(1→4)-linked glucose units, stabilized by inter- and intramolecular hydrogen bonds between hydroxyl groups and oxygen atoms [47]. BC is an environmentally friendly polymer with high crystallinity (80-90%), mechanical strength (49-422 MPa), and water retention (up to 1000%), owing to extensive hydrogen bonding [48,49]. Its ultrafine nanofibrous network, renewability, biocompatibility, and abundant hydroxyl groups make BC a promising biosorbent for heavy metal ions. Functionalization, such as grafting diethylenetriamine, can enhance metal chelation, though adsorption capacity often remains limited. BC-based composites have further improved performance, demonstrating enhanced heavy metal removal and potential for wastewater treatment [50].

3. BC Modifications for Composite Formation

Composites consist of a matrix supporting a reinforcement material, which imparts specific physico-chemical and biological properties [51]. BC nanocomposites are formed via modification techniques that enhance stability, porosity, and functionality [52]. BC composites have been developed with natural and synthetic polymers, inorganic nanoparticles, metals, metal oxides (Figure 2(a)), clays, and carbon-based nanomaterials, including graphene and carbon nanotubes (Figure 2(d)) [33,52,53] as some of them are mentioned in Table 2. Such reinforcements can confer conductivity, antimicrobial activity, or enhanced adsorption, applied through in situ synthesis, mixing, printing, doping, or coating methods.

Table 2. Different composite materials increase physical and mechanical characteristic of BC for removal from wastewater pollutants.

Composite materials	Reinforcing agents	Modification /Synthesis approach	References
Metal-Oxide Nano-particle	ZnO Nano-particles	2% of ZnO were scattered in H_2O by sonication. This suspension was immersed with BC hydrogel for 24 hours. The composite hydrogel was splashed and freeze-dried.	[54]
Metal-Oxide Nano-particles	TiO_2 and ZnO Nano-particles	BC was incorporated with TiO_2 nanoparticles into 50% ethanol, then mixture was blended with $Zn(NO3)_2•6H_2O$ and NaOH, stir for 24 hours, and dry at room temperature.	[55]
Nanoparticles	Bi_2MoO_6	Bi_2MoO_6 was mixed with BC and stirred for 12 hours. The composite was splashed and dried.	[56]
Metals-Organic Framework (MOF)	Iron-based MOF	MIL-100(Fe)@BC was synthesized by refluxing a mixture of iron(III) chloride and benzene tricarboxylate in sonicated BC at 100°C, followed by centrifugation, freeze-drying, and activation.	[57]

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Magnetite Nanoparticles (MNPs)	$(FeCl_2 \cdot 4H_2O)$ $(FeCl_3 \cdot 6H_2O)$	Disperse 500 mg of BC into 100 ml volume solution of de-ionized water $(FeCl_2 \cdot 4H_2O)$, $(FeCl_3 \cdot 6H_2O)$. Stirred solution for 15 min, and then during the stirring 50 mL of NaCl for further 1 hour at 25 °C. Finally, 200 mL of NH_4OH (30% V/V) was dispersed while stirring for 15 min, then washed, collected, and air-dried.	[58]
Magnetite Nanoparticles	Fe_3O_4	BC membranes were produced by Gluconacetobacter Strain in a modified HS medium. Its nanoparticles deposed on BC membranes were synthesized by coprecipitation method. The resulting BC-Fe_3O_4 composites, washed and dried at room temperature.	[59]
Polymers	Polyethyleneimine (PEI_3)	BCB@PEI_3 composites were successfully biosynthesized by suspending of bacterial strain *Kosakonia oryzendophytica FY-07* in the fermentation medium. Following a 24 hours static fermentation, the resultant BC membrane was crosslinked with $PEI3_3$. The resulting BCB@PEI_3 were washed by deionized water and freeze-dried for subsequent characterization.	[60]
Magnetite composites	Fe_3O_4	Fe_3O_4/BC composite is synthesized by the in-situ coprecipitation method. Where the BC membrane was immersed in Fe (II) / Fe (III) sulphate solution under N_2 gas, followed by NaOH addition to induce magnetite deposition. The composites were then rinsed and dried to a constant weight.	[61]

BC has been composited by biopolymers such as alginate, chitosan, starch, hyaluronic acid, collagen, keratin, gelatin, PLA, and PHA, as well as synthetic polymers including PVA, PANI, and PAEM [62]. BC composites have also incorporated biomolecules, enzymes, antibiotics, amino acids, peptides, hormones, and cells to extend functionality [63,64]. Magnetic nanomaterials, including metal and metal oxide nanoparticles, provide unique magnetic properties for manipulation and localized effects [65]. For example, an electromagnetic BC composite was produced by culturing *Gluconacetobacter xylinus* with magnetite nanoparticles, followed by in situ polyaniline polymerization, combining magnetic and conductive properties [66] (Figure 2(b)).

BC serves as a porous, hydrophilic matrix, with its nanofibrous network enabling the incorporation of nanoparticles and other functional materials. Indeed, BC composition helpful boost its applications; however, current literature is primarily concentrated on the addition of organic functional groups to the BC composite [33,67]. Functionalization with organic groups, such as diethylenetriamine, enhances metal ion adsorption, while embedding nano adsorbents into BC overcomes challenges of low solubility and difficult recovery [68]. In situ preparation allows metal or polymer nanoparticles (Figure 2(c)) to be integrated into the BC matrix without disrupting its three-dimensional nanoporous structure, providing a versatile platform for high-capacity, recyclable heavy metal removal [69].

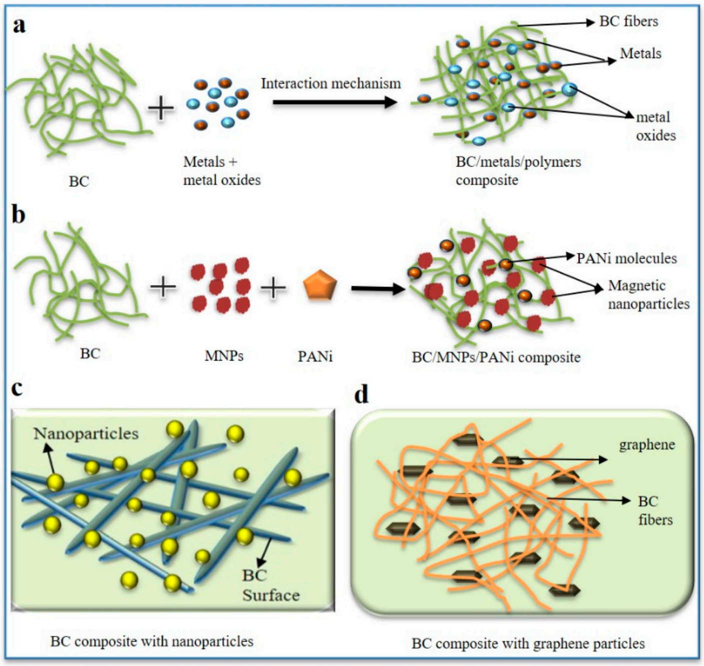

Figure 2. BC composites with **(a)** metal oxide [70] **(b)** electromagnetic nanocomposites [66] **(c)** nanoparticles(NPs) [69] **(d)** graphene molecules.

4. BC Modification

BC, with chemistry similar to plant cellulose but superior physical properties, has been widely used in composite materials. Its abundant surface hydroxyl groups enable diverse modifications: surface functionalization, chemical or biological modification, nanoparticle incorporation, physical treatments, and composite formation to enhance heavy metal adsorption [69]. In particular, in situ composite formation, leveraging BC's biotechnological production, provides an efficient strategy to improve metal-binding capacity and contaminant removal [71].

4.1. Surface Modification

BC has abundant surface hydroxyl groups that facilitate blending with other materials, enhancing composite properties [72,73]. However, hydrogen bonds with reinforcing agents are often weak, and converting hydroxyls to carboxyl or carboxylate groups improves crosslinking and composite stability [74–78]. Common strategies include hyaluronic acid immersion and carboxymethylation, which introduce functional groups to enhance metal adsorption. Oxidation with TEMPO under harsher conditions achieves similar effects. Hydrophilicity can also be transformed to hydrophobicity via alkoxysilane hydrolysis and surface modifications, creating porous, superhydrophobic BC membranes suitable for applications such as water oil separation [79]. Some surface modification methods are highlighted in (Figure 3(c)).

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4.2. Chemical Modification

Biosynthetic modification of BC is sustainable but limited by fermentation constraints and additive microfibril interactions. Chemical modifications, including carboxymethylation, acetylation, and phosphorylation, provide greater flexibility, introducing functional groups that enhance hydrophobicity, ion adsorption, and optical properties while preserving BC's nanonetwork and mechanical strength [62]. Functionalized derivatives such as diethylenetriamine-BC (EABC), amidoximated-BC (Am-BC), and phosphorylated BC maintain the microporous structure and exhibit improved metal ions adsorption [80,81]. Chemical modification is also carried out using in-situ and ex-situ methods for synthesis of BC nanocomposite, as depicted in (Figure 3(a-b)) [52]. TEMPO-mediated oxidation introduces carboxylate groups under mild aqueous conditions, anchoring metal ions without altering crystallinity or crystal size [69,82].

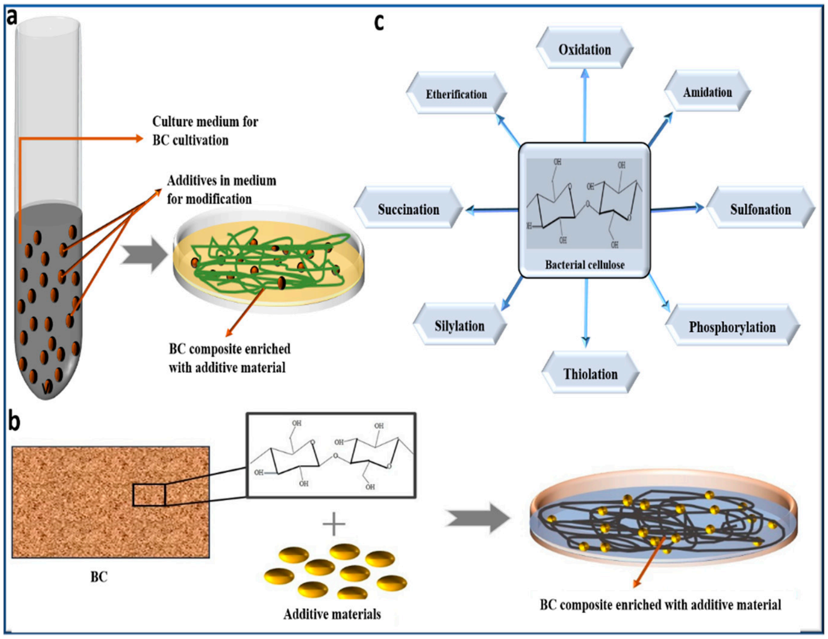

Figure 3. BC modification methods **(a)** ex-situ **(b)** in-situ [52] and **(c)** Surface modification [24].

4.3. Biosynthetic Modification

The morphology and supramolecular structure of bacterial cellulose (BC) can be modified through cultivation situations, including strain selection, carbon source, and media additives (Figure 4(a)) [69,72]. Additives influence BC assembly, affecting crystallinity, ribbon width, pore structure, water content, and mechanical properties. For example, antibiotics such as nalidixic acid increase ribbon width, while reducing agents like dithiothreitol narrow it. Polymers such as CMC, HPMC, MC, PVA, and PEG modify crystallinity, porosity, and water retention, enhancing ion adsorption and thermal stability. Functionalized BC demonstrates improved heavy metal adsorption, highlighting the potential of additive-mediated control during biosynthesis [76,83–85].

4.4. Nano-Fibrillated Bacterial Cellulose (NFBC)

Nano-fibrillated Bacterial Cellulose (NFBC) consists of elongated fibers (>17 μm) with diameters around 20 nm, providing a high aspect ratio and enlarged specific surface area, favorable for adsorption [86]. While NFBC lacks inherent metal-binding groups, surface hydroxyls can be functionalized, for example, with EDTA (ethylenediaminetetraacetic acid), to enable efficient heavy metal removal. EDTA-grafted NFBC (EDNFBC) (Figure 4(b)) demonstrates enhanced adsorption capacity, highlighting the potential of surface-modified CNFs as effective biosorbents [87–91].

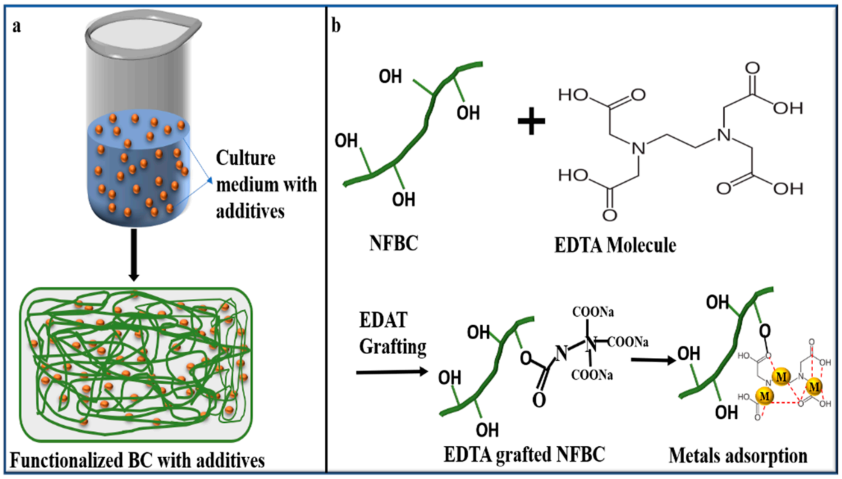

Figure 4. **(a)** Biosynthetic modification. **(b)** EDTA grafted NFBC for metals adsorption [91].

5. Heavy Metals Adsorption/Removal from Water

Heavy metal elements with atomic numbers >20 and densities ≥5× that of water, such as Cu, Cr, Cd, Pb, pose serious environmental and health risks, including cancer, neuromuscular disorders, and metabolic failure [61,92]. Removal strategies include bioremediation, chemical precipitation, membrane filtration, adsorption, phytoremediation, and microbial conversion [4,5,7,93–95]. BC and BC-based composites have emerged as effective adsorbents, with reinforced composites enhancing metal-binding through carboxylate and amine groups via coordination, ion exchange, and electrostatic interactions [25,32,96,97]. Examples include BC-attapulgite magnetic composites for Cr^{6+} and Cu^{2+} (91 and 70.5 mg/g, respectively) [25] and poly(amidoxime)-BC aerogels for Pb^{2+}, Cu^{2+}, Zn^{2+}, Mn^{2+}, and Cd^{2+} (382-571 mg/g) [97]. Functionalization, such as carboxymethylation, further improves adsorption, as demonstrated for Pb^{2+} (50.2 mg/g within 60 min) [98]. Table 3 represented some applications of composite for metal removal.

Table 3. Different BC-based composites for heavy metals contaminated.

Composite types	Removal method	Target metals	Removal Capacity (mg/g)	References
MIL100(Fe) (a)@BC Nanocomposite	Adsorption	As(III)	4.81 mg/g	[57]
ZIF-67/BC/CH(b) composite aerogels	Adsorption	Cu^{2+} and Cr^{6+}	Cu^{2+}:200.6 mg/g, Cr^{6+}:152.1 mg/g	[96]
Magnetic composite ATP@(BCNs/CS)$_7$(c)	Adsorption	Pb^{2+}, Cu^{2+}, and Cr^{6+}	Pb^{2+}:66.4 mg/g, Cu^{2+}: 71.2 mg/g, Cr^{6+}:85 mg/g	[25]
Fe_3O_4/BC nanocomposites	Adsorption	Pb^{2+}, Mn^{2+}, and Cr^{3+}	Pb^{2+}:65 mg g^{-1}, Mn^{2+}:33 mg/g, Cr^{3+}:25 mg/g	[29]
BC-magnetite composites	Adsorption	Cr(VI)	〃	[59]

PAO(d)/BC composite aerogel	Adsorption	Pb^{2+}, Cu^{2+}, Zn^{2+}, Mn^{2+} and Cd^{2+}	Pb^{2+}:571.5 mg/g, Cu^{2+}:509.2 mg/g, Zn^{2+}:494 mg/g, Mn^{2+}:457.2 mg/g, Cd^{2+}:382.3 mg/g	[97]
Carboxymethylated Bacterial cellulose	Adsorption	Pb^{2+}	Pb^{2+}:59.5 mg g^{-1}	[98]
BCB@PEI$_3$(e) composite	Adsorption	Cd^{2+}, Pb^{2+}, Cu^{2+}	Cd^{2+}:169.19 mg g^{1}, Pb^{2+}:156.13 mg/g, Cu^{2+}147.2 mg/g	[60]
BCM-nZVI(f) composite	Adsorption	Cd^{2+}	134.0 mg/g	[99]

[Material Institute Lavoisier-100(Iron)(MIL)-100(Fe)(a), imidazolate framework-67(ZIF-67)/chitosan (CH)(b), attapulgite(ATP) BC nanofibrils chitosan(BCNs/CS))(c), polyamidoxime (PAO)(d), bacterial cellulose-bentonite@polyethylenimine (BCB@PEI)(e), nanoscale zero-valent iron onto BC membranes (BCM-nZVI) (f)]

5.1. Adsorption/Removal Mechanism of BC

In wastewater treatment, adsorption is a promising approach for heavy metal removal. Three-dimensional nanofibrous network of BC provides increased surface area and diverse porosity, facilitating adsorption [100] as (Figure 5(a)) represents the general adsorption mechanism by cellulose based materials. Functional groups, including methoxy, amide, phenolic, thiol, carbonyl, and carboxyl act as electron donors, forming stable complexes with metal ions by hydrophobic interactions, hydrogen bonding, and coordination [100–102]. Integration of functional groups into BC enhances adsorption capacity, with the detailed adsorption mechanisms extensively described in the literature [103,104].

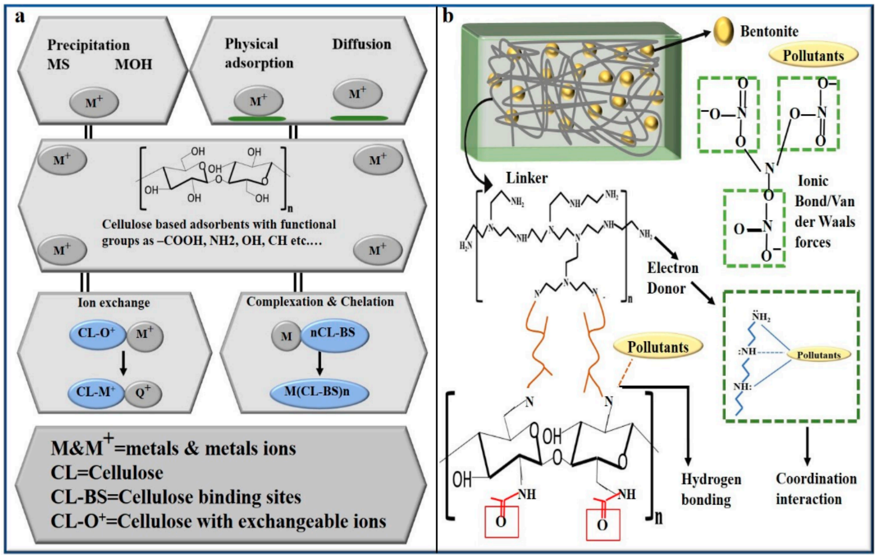

Figure 5. Illustration of the adsorption mechanism in **(a)** Cellulose-based materials [24] **(b)** BCB@PEI composite [60].

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Zhao et al. developed BC bentonite@polyethylenimine (BCB@PEI) composite membranes for water treatment combining structural durability, high surface area, and enhanced adsorption sites [60]. Bentonite contributed -OH and aluminum oxide groups for ionic and van der Waals interactions, PEI provided -NH_2 /-NH_3^+ groups for metal coordination, and BC offered -OH and -NHC=O groups for hydrogen bonding and electrostatic interactions (Figure 5(b)). The synergistic effect of these components improved the heavy metals and organic dyes adsorption, illustrating the benefit of multi-component BC-based composites [60,105].

5.1.1. Adsorption Mechanism of Lead Ions

Adsorption of Pb(II) onto BC-hydroxyapatite (BC-HA) nanocomposites (Figure 6(a)) involves ions exchange, electrostatic interactions, and complexation [106]. In BC, abundant hydroxyl groups provide active sites, but weak electrostatic interactions limit adsorption capacity [107]. Incorporating HA enhances adsorption by introducing additional cation-exchange sites via calcium ions, which readily bind Pb(II) due to similar ionic radius and high electronegativity. Complexation with hydroxyl protons further contributes to Pb(II) removal, collectively improving the efficiency of the BC-HA composite [108].

5.1.2. Adsorption Mechanism of Copper Ions

Xiaorui et al. reported that Cu(II) adsorption by copper-ion imprinted BC (IBCN-Cu) occurs via chemisorption, involving coordination between Cu(II) ions and BC hydroxyl groups (Figure 6(b)). This chelation creates valence interactions, while the imprinting process generates specific adsorption sites complementary in charge, size, shape, coordination number, and spatial arrangement, conferring high selectivity and resistance to interference for Cu(II) ions [46].

5.1.3. Adsorption Mechanism of Cadmium Ions

Cheng et al. described cadmium removal by BC-nZVI composites (BCM-nZVI), where reduction dominates Cd^{2+} adsorption (Figure 6(c)). Direct reduction of Cd^{2+} by Fe^{2+} is limited due to similar redox potentials (Fe^{2+}, $E_0 = -0.41$ V; Cd^{2+}, $E_0 = -0.40$ V). In aqueous solutions, Fe^0 generates hydrated electrons ($E_0 = -2.91$ V), which reduce Cd^{2+} to insoluble, non-toxic Cd^0, deposited on the composite. Concurrently, nZVI oxidizes to Fe^{2+}/Fe^{3+}, forming surface iron oxides (Fe_2O_3, Fe_3O_4, FeOOH), and the solution pH rises to ~8.8, indicating OH^- formation [99].

5.1.4. Adsorption Mechanism of Chromium Ions

Qiao et al. described Cr(VI) remediation using BC-nZVI composites [109] (Figure 6(d)). Cr(VI) is chemisorbed via surface pores and oxygen-containing groups, then reduced to Cr(III) through direct electron transfer from nZVI and indirect transfer via BC. The nZVI-BC system continuously generates [H] and Fe^{2+}, accelerating Cr(VI) reduction while Fe^{2+} oxidizes to Fe^{3+}. Some Cr(III) is initially repelled electrostatically, but interaction with negatively charged CMC-nZVI@BC (carboxymethyl cellulose loaded on biochar) converts repulsion into stable complexes with iron, attraction, and surface functional groups.

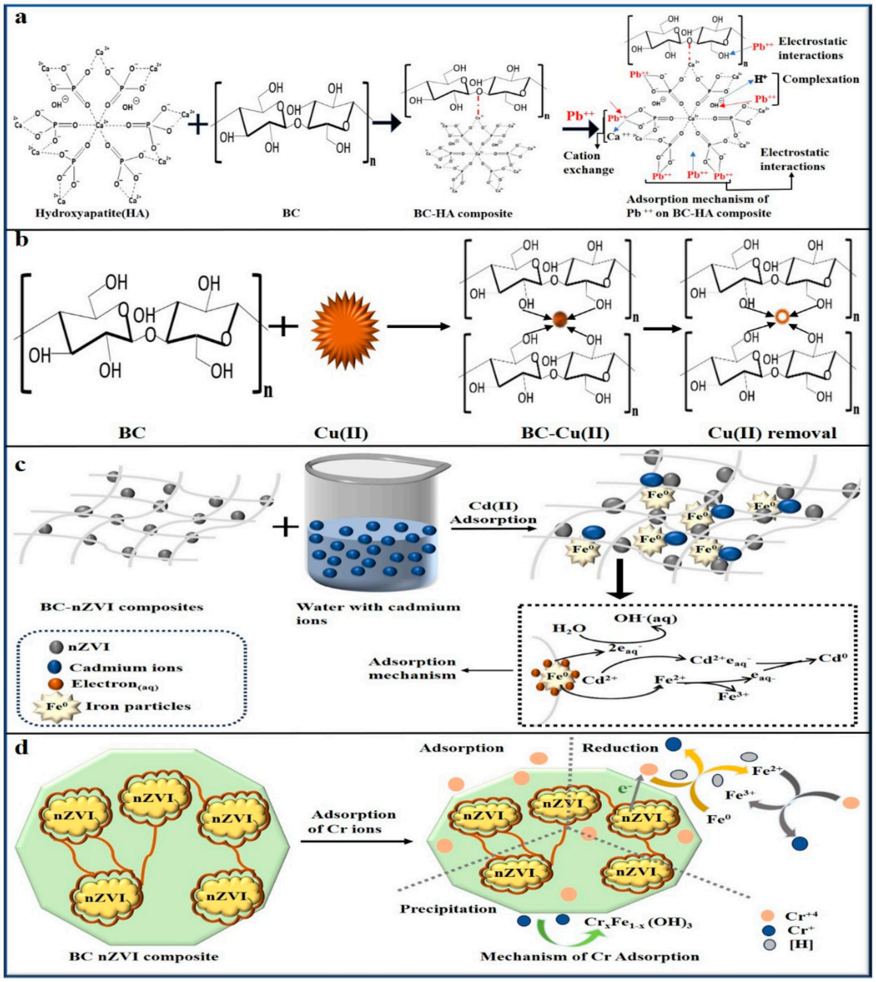

Figure 6. Adsorption mechanisms of metal ions such as**(a)** Pb(II) ions [106]. **(b)** Cu(II) ions [46] **(c)** Cd(II)ions [99] **(d)** Cr(VI) ions. [109].

5.2. Adsorption Performance of BC Composites Toward Heavy Metals

Adsorption capability of BC composites for heavy metals increases with initial ion concentration until reaching equilibrium, demonstrating excellent removal performance [99,110]. Increasing the adsorbent dosage further enhances removal, as more active sites become available for metal ion binding.

Adsorption isotherms of BC composites for heavy metals were generally analyzed by using Langmuir, Freundlich models, and Sips isotherms (Figure 7(a)) [99,109]. Time-dependent studies show rapid uptake: Pb^{2+} and Cu^{2+} reach 99% removal within 15 min and equilibrium by 20 min, while Mn^{2+}, Cr^{2+}, and Cd^{2+} reach equilibrium within 25 min with 70-85% removal (Figure 7(b)) [97]. Low-dose BC composites ($0.5\,g\,L^{-1}$) achieve high removal efficiency in <30 min, demonstrating their suitability for fast water purification. Adsorption kinetics fit both pseudo-first-order and pseudo-second-order models with high correlation ($R^2 > 0.9997$), indicating chemisorption as the dominant mechanism. Rapid kinetics are attributed to hierarchical porous channels, facilitating dynamic diffusion to active sites [97,109,111]. The nonlinear equations can describe the adsorption process:

$$q_t = q_e(1 - e^{-k_1 t}) \quad (1)$$

$$q_t = \frac{k_2 q_e^2 t}{1 + k_2 q_e t} \quad (2)$$

Here, q_e and qt (mg/g) are the adsorption capacities at equilibrium and t time, respectively, and k_1 (1/h) and k_2 (gm/g/h) are the rate constants [106,112,113].

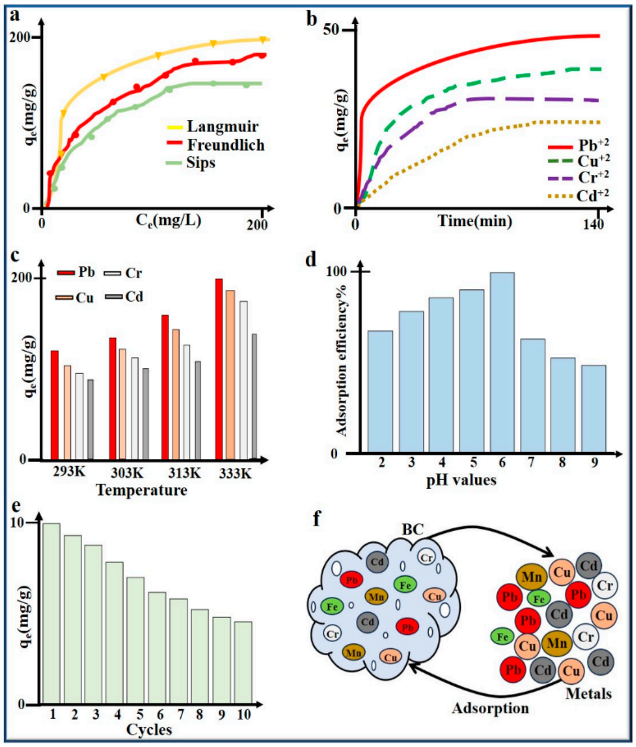

Figure 7. **(a)** Langmuir, Freundlich, and Sips isotherms [109] **(b)** Adsorption Kinetics of various metal ions [97] **(c)** Effect of temperature [60] **(d)** pH [97] **(f)** Recyclability of BC composites for the adsorption of metals [60] **(f)** Adsorption of metals by BC composite.

Adsorption of heavy metals is strongly pH-dependent [99,110,114]. Solution pH influences both the surface charge and the metal ions adsorbent. For BC composite aerogels, removal efficiencies of Pb(II), Cu(II), Zn(II), Mn(II), and Cd^{2+} increase with pH from 2 to 6, reaching a maximum at pH 6, and show weak dependence beyond this range, indicating broad pH applicability [97] (Figure 7(d)). At pH <pHPZC (point of zero charge), adsorbent surfaces are positively charged, reducing metal uptake due to electrostatic repulsion. In contrast, at pH >pHPZC, deprotonation of hydroxyl and amino groups generates negative charges, enhancing adsorption via electrostatic interactions and complexation [115,116]. To avoid metal hydroxide precipitation, pH 6 is typically selected for subsequent studies [117]. These composites are effective for water treatment across varying pH conditions [60,110].

The adsorption capacity of BC composites increases with temperature (Figure 7(c)) as elevated thermal energy enhances ion mobility and contact with active sites. Thermodynamic investigation exposed negative $\Delta G°$ values, confirming spontaneity, and a positive $\Delta H°$ (~59.7 kJ/mol), indicating endothermic chemisorption. The positive $\Delta S°$ (~46.0 J/mol/K) enhance interaction at the solid-liquid interface. Together, these parameters demonstrate that higher temperatures favor heavy-metal removal and broaden the operational tolerance of BC composites [60,109,118–120].

6. Reusability of the BC Composites

Recyclability is critical for the practical application of adsorbents. BC composites retain >80% of their initial adsorption capacity for Cd^{2+}, Pb^{2+}, Cr^{2+} and Cu^{2+} after 10 cycles (Figure 7(e)), demonstrating excellent reusability and cost-effectiveness [60,91]. Similar studies report that modified BC-based composites maintain ~79% efficiency after repeated use [121–123], underscoring their potential for sustainable wastewater treatment (Figure 7(f)).

7. Conclusion and Future Perspective

Bacterial cellulose (BC) and its composites are emerging and effective materials for heavy metals, dyes, and organic pollutants from aqueous environments. Their three-dimensional polymeric networks, rich in hydrophilic groups, provide large surface areas and abundant binding sites, enabling interactions via, hydrogen bonding, electrostatic attraction, and van der Waals forces. Nano-cellulosic BC composites combine biodegradability, low toxicity, biocompatibility, reusability, and increased adsorption capacity, making them equally cost-effective and environmentally sustainable. Adsorption typically follows Langmuir or Freundlich isotherms, with kinetics described by pseudo-first- or second-order models, reflecting predictable and efficient performance.

Despite these advantages, the higher cost of BC production and chemical functionalization compared with conventional adsorbents remains a challenge. Future efforts should focus on scalable, cost-efficient fabrication, optimized regeneration cycles, and detailed structural and mechanistic characterizations to establish structure–activity relationships. Integrating theoretical modeling with experimental studies will further enable the rational design of high-performance composites. Collectively, BC-based materials offer a versatile, sustainable, and industrially viable platform for next-generation water remediation technologies.

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