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Review

Waste-to-Nano adsorbents: Circular conversion of agro-industrial residues for water remediation

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Abstract: Waste-derived nanoadsorbents are emerging as a strategic class of circular economy materials that transform agricultural residues, food-processing by-products, municipal biowaste, and mineral-industrial residues into high-surface-area adsorbents for water purification. This review compiles and summarizes the recent research related to the design, characterization, adsorption capacity, regeneration and environmental translation of sustainable nanoadsorbents that are derived from waste. The manuscript emphasizes the carbonaceous nanomaterials, biochar magnetic hybrids, egg-shell and zeolite-based composites, chitosan, carbon-dot membranes, cellulose nanomaterial architectures, green-synthesized metals, metal-oxide nanostructures, and geopolymers. Specific contaminants of concern (COCs) such as nickel, cadmium, chromium, lead, dyes, antibiotics, per- and polyfluoroalkyl substances (PFAS) related compounds, and microplastics receive special attention. The review demonstrates that, when precursor chemistry, activation process, nanoscale morphology, surface functionality and regeneration method are optimized together, the uptake of pollutants by Waste-to-Nano Adsorbents (WNAs) can be enhanced to a high level. The full-scale implementation is limited due to the heterogeneity of the feedstock, the lack of complete life cycle assessment, inconsistent adsorption testing, risk of particles releasing from the material and limited field validation. The main message is that Waste-to-Nano Adsorbents (WtNA) should be evolved to be a platform rather than a series of stand-alone laboratory demonstrations, encompassing green synthesis, mechanistic characterization, circular regeneration and techno-economic assessment.

Keywords: waste-derived nanoadsorbents; circular nanotechnology; wastewater remediation; biochar nanocomposites; eggshell waste; cellulose nanomaterials; magnetic adsorbents; green synthesis

1. Introduction

The special issue in Characterization and Application of Nanomaterials is specifically dedicated to the sustainable conversion of agro-waste and industrial residues into value-added nanomaterials, with a focus on the application principles of the circular economy, purification of water resources, and removal of pollutants, scalability, cost-effectiveness and environmental impact. This review thus not only

addresses a materials-chemistry field of research, but rather regards waste-derived nanoadsorbents as a crossover field of waste valorization, characterization of nanomaterials, and environmental remediation [1].

Pharmaceutical contaminants such as diclofenac are increasingly detected in aquatic environments due to their extensive consumption and persistence, creating a need for efficient treatment technologies. Magnetic biosorbents provide a promising strategy for contaminant removal because they combine biological adsorption capability with magnetic separation, enabling efficient recovery of the adsorbent after water treatment [2].

Sustainable adsorbents are required because many pollutants, such as heavy metals, dyes, antibiotics, phenolic compounds, per- and polyfluoroalkyl substances (PFAS), PFAS-type contaminants and microplastics, are persistent in aquatic environments and cannot be effectively treated by conventional treatment units, which can be expensive, energy-intensive or be inadequate for the treatment of emerging pollutants [3-5]. High accessible surface area, tunable pore structure, functional groups and short diffusion paths are advantages that nanoscale adsorbents offer, however the benefits of the synthesis input, re-regeneration and end-of-life pathways are not necessarily compatible with a circular production process [6-8].

Waste-derived nanoparticles and nanocomposites are particularly attractive because precursor chemistry is already well endowed with precursors such as carbonates, silicates, lignocellulosic polymers, chitin/chitosan, proteins, inorganic oxides, and transition-metal-bearing phases that can be converted to adsorption-active materials [9-11]. Eggshell waste, for instance, can supply calcium carbonate and porosity that renders the surface; biomass-derived biochar can offer aromatic carbon networks and oxygen-containing functionalities; chitosan can deliver amine-rich chelating domains; and cellulose nanomaterials can provide mechanoactive properties and functional surfaces that are hydrophilic [12].

Nano-adsorbent design demonstrates that combining engineered surface functionalities with sustainable material synthesis strategies can improve contaminant removal efficiency, many high-performance nanoadsorbents rely on costly precursors and complex synthesis routes, highlighting the need for sustainable approaches that integrate waste valorization with nanomaterial development. Waste-derived nanomaterials represent an emerging pathway to produce functional adsorbents while simultaneously addressing waste management challenges and promoting circular resource utilization [13].

Recent studies have demonstrated the potential of agro-industrial residues as sustainable precursors for the fabrication of advanced nano-adsorbents. Baruah et al. developed nanocellulose iron oxide nanobiocomposites (NIONs) using rice husk and sugarcane bagasse-derived nanocellulose for arsenic-contaminated groundwater remediation. The resulting nanobiocomposites exhibited superparamagnetic behavior, enabling facile magnetic separation and recyclability. By integrating response surface methodology (RSM) and artificial neural network (ANN) modeling, the adsorption process was optimized, achieving approximately 99% arsenic removal under optimized conditions. These findings highlight the feasibility of converting agricultural waste into functional magnetic nano-adsorbents for sustainable water treatment applications [14].

Although the number of publications has increased rapidly, there is a need for the field to overcome the reproducibility problem. The variations in feedstocks, pyrolysis/activation conditions, size and surface area reporting and adsorption conditions, as well as the lack of reuse testing, make the direct comparison of materials difficult [15].

The rapid growth of industrialization, urbanization, and agricultural activities has significantly increased the generation of solid waste and the contamination of water resources. Agro-industrial residues, such as rice husks, coconut shells, sugarcane bagasse, corn cobs, banana peels, sawdust, and fruit wastes, are often discarded through landfilling or open burning, leading to environmental pollution and greenhouse gas emissions. At the same time, wastewater contaminated with heavy metals, dyes, pharmaceuticals, pesticides, and other emerging pollutants poses serious risks to ecosystems and human health. Developing sustainable technologies that simultaneously address waste management and water pollution has therefore become a global priority [16].

One promising solution is the conversion of agro-industrial residues into nano-sized adsorbents. This waste-to-resource approach aligns with the principles of the circular economy by transforming low-value biomass into high-performance materials for environmental remediation. Nano adsorbents derived from agricultural wastes exhibit high surface area, abundant functional groups, tunable pore structures, and excellent adsorption capacity, making them effective for removing a wide range of contaminants from water [17].

The critical review for the current special issue should thus have to combine synthesis, characterization, adsorption performance, constraints for regeneration and deployment in a single evidence framework [18].

The aim of this manuscript is to determine the most promising architectures of waste-to-nano adsorbents, gather actual performance data from recent research, reproduce results and tables cited from open access sources where possible (and permitted by licensing), and present a roadmap to translation for high-value waste remediation applications. The review does not seek to be exhaustive, but rather to point to studies that have clearly identified waste precursors, reasonably understandable waste characterization, adsorption data for the pollutants and credible evidence of circularity or regeneration [19].

2. Materials and Methods

The manuscript was organized as a narrative review, and a literature search of the last five years was performed in PubMed, NCBI, PubMed Central, MDPI, Springer Nature, BMC, Springer, Open, and chemistry and environmental science databases. The keywords used in the search included: Waste-derived nanomaterials, Nanoadsorbents, biochar, Eggshell waste, chitosan, carbon dots, cellulose nanomaterials, magnetic nanocomposites, geopolymers, wastewater treatment, heavy metals, dyes, antibiotics, per- and polyfluoroalkyl substances (PFAS) and remediation. The evidence that was deemed acceptable was given more weight if the article provided a synthesis or modification procedure that could be reproduced, a defined waste precursor, material characterization by at least two different

techniques Fourier-transform infrared spectroscopy (FT-IR), Scanning electron microscopy (SEM), X-ray diffraction (XRD), Brunauer-Emmett-Teller surface-area analysis (BET), Zeta potential), adsorption or degradation performance with pollutant concentration and contact time, and some indication of regeneration or mechanism. This weighting exemplifies the perspective that a nanoadsorbent cannot be deemed to be environmentally ‘mature' unless mechanistic interpretation and reuse evidence is available.

3. Results and evidence synthesis

It highlights the conversion of circular waste to nano, priority water contaminants, agro-industrial residues, engineered carbon, oxide, hybrid nanomaterials, and scalable remediation. These components are a perfect match with the special issue priorities of agro-waste valorization, industrial waste utilization, low-cost nanomaterials, circular economy, sustainable nanotechnology, environmental remediation and nanomaterial characterization **Table 1** [20].

All of the above evidence shows that engineered nanoadsorbents produced from agricultural, food, biological, and industrial wastes can be effective in significantly improving the removal of contaminants and, at the same time, valorize the waste streams. It was revealed that pyrolysis, hydrothermal synthesis, sol–gel processing, co-precipitation, combustion and ball milling could convert the heterogeneous wastes into functional materials such as adsorption material, photocatalytic degradation material, electrochemical treatment material, and advanced oxidation material for aqueous pollutants [21]. The eggshell–zeolite (EZ) and the iron-functionalized eggshell–zeolite (FEZ) nanoadsorbents were found to have maximum $^{+}Ni^{2}$ adsorption capacities of 321.1 and 287.9 mg g^{-1}, respectively, with a removal efficiency of 99.9% and 97.3%, respectively, the adsorption being spontaneous and endothermic, while their performance was maintained after repeated adsorption, desorption cycles, thus providing meaningful reusability [22]. The immobilization of waste-derived carbon dots in a recoverable chitosan membrane showed rapid $^{+}Cd^{2}$ uptake, reaching equilibrium in ~5 min at 25 °C and pH 8, a maximum adsorption capacity of 112.4 mg g^{-1} and ~93% removal under UV illumination [23]. A Springer scientometric analysis of 2,673 publications released between 2011 and 2022 identified magnetic biochar, heavy-metal removal, dye adsorption, pyrolysis and nitrogen modification as persistent research fields, indicating the increasing significance of precursor activation and the functionalization of the surface [24]. In line with these observations, the review carried out by the RSC finally concluded that the high specific surface area, high surface reactivity, tenability of porosity and tunability of function of carbonaceous, metal-oxide, magnetic, polymeric and hybrid nanoadsorbents make them efficient for removal of multiple heavy-metal ions, but systematic assessment of regeneration, nanoparticle leaching, ecotoxicity, treatment cost, selectivity in complex water matrices and pilot- or field-scale performance is still needed for implementation of these adsor-bents. Together, these results suggest that adsorption properties are not enough to establish environmental superiority—the most promising waste-derived nanoadsorbents should also be recoverable, multi-

cycle stable, have low-toxicity synthetic methods, minimal secondary release, and proven to be useful in real wastewater [4,7,10,11].

3.1. The function of the adsorbents depends upon waste precursor chemistry

Structural or chemical features that are already present in the precursors to waste are most likely to be effective. Eggshell waste can be functionalized for an amine-rich adsorption site; a porous biochar or a nanocellulose-based adsorbent can be used, and chitosan-based matrices can be used as a calcium-carbonate source, a porous biochar, or as a source for amine-rich coordination sites for metal ions [10].

In the context of biomass and biochar research, the conversion route is responsible for aromaticity, ash fraction, oxygenated functional groups, magnetism and porosity [12]. Reviewed 2673 papers published in the Web of Science database from 2011 to 2022, and identified magnetic biochar, heavy metal and dye adsorption, pyrolysis, and nitrogen modification as ongoing research clusters, highlighting the importance of the activation of biochar precursors and functionalization in improving biochar performance for wastewater treatment [10].

The cellulose nanomaterials are a unique waste-to-nano platform as they can be processed into membranes, aerogels, hydrogels, sponges, and microspheres with a combination of nanoscale surface area and macroscopic processability. Nanocellulose is of special interest in adsorption applications where the use of fixed beds, membranes or monoliths that can be reused instead of dispersible nanoparticles is desirable **Table 1** [10].

Table 1. Directly reproduced keyword-cluster evidence from a Springer Nature open-access scientometric review of biochar adsorption for wastewater treatment.

Cluster ranking	Number of nodes	Mean contour value	Average year	Main content
0	33	0.881	2012	Magnetic biochar; graphene oxide; Pb(II)
1	27	0.931	2012	Tetracycline; hexavalent chromium; nanoparticle
2	22	0.964	2012	Heavy metal; cadmium; zinc
3	21	0.981	2012	Degradation; dye; desorption
4	21	0.910	2011	Adsorbent; methylene blue; kinetics
5	19	0.955	2012	Temperature; behaviour; steam
6	17	0.980	2012	Biochar; charcoal; organic matter
7	16	0.920	2012	Biosorption; crop residue; slow pyrolysis
8	12	0.915	2012	Adsorption; mechanism; copper
9	12	0.966	2012	Pyrolysis; nitrogen; manure

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3.2. Eggshell-waste nanocomposites as high-capacity nickel adsorbents

One of the most directly relevant studies for the special issue is the MDPI Nanomaterials article by Segneanu et al. (2023) [9], which engineered two composite nanoadsorbents from eggshell waste, zeolite and iron for nickel removal. The work is valuable because it connects a recognizable food/agro-industrial waste stream to real adsorption metrics, structural characterization and regeneration outcomes.

The study reported that Iron-functionalised eggshell-zeolite nanoadsorbent (FEZ) and Eggshell-zeolite composite nanoadsorbent EZ achieved high nickel adsorption capacities of 321.1 mg/g and 287.9 mg/g, respectively, with removal efficiencies of 99.9% for Iron-functionalised eggshell-zeolite nanoadsorbent (FEZ) and 97.3% for Eggshell-zeolite composite nanoadsorbent EZ under optimized conditions. The same study reported that desorption reached 91% for Iron-functionalised eggshell-zeolite nanoadsorbent (FEZ) and 89% for Eggshell-zeolite composite nanoadsorbent EZ using nitric acid, and that adsorption capacity decreased only approximately 10-12% after ten adsorption-desorption cycles (**Tables 2–5**).

The mechanistic strength of this work lies in its combined use of Fourier-transform infrared spectroscopy (FT-IR), Scanning electron microscopy (SEM), X-ray diffraction (XRD), Brunauer-Emmett-Teller surface-area analysis (BET), adsorption isotherms, thermodynamic assessment and kinetic modelling. The Freundlich model gave slightly stronger fitting than Langmuir, suggesting heterogeneous multilayer adsorption, whereas kinetic values were closest to experimental capacities under the pseudo-second-order model, pointing to chemical-interaction contributions alongside physical adsorption (**Figures 1–3**) [9].

Table 2. Directly reproduced Langmuir and Freundlich parameters for nickel adsorption on Iron-functionalised eggshell-zeolite nanoadsorbent (FEZ) and Eggshell-zeolite composite nanoadsorbent EZ.

Adsorbent	Qe,exp (mg/g)	Qm (mg/g)	k	RL	Langmuir R2	KF	n	Freundlich R2	Ea (kJ/mol)
FEZ	321.1	321.0	0.283	0.861	0.9994	4.60517	1.893	0.9999	32.4
EZ	287.9	286.8	0.223	0.783	0.9989	3.85721	1.659	0.9998	32.2

Source note: Reproduced in editable form from [9], Nanomaterials, https://doi.org/10.3390/nano13182572; CC BY 4.0.

Table 3. Directly reproduced thermodynamic parameters for nickel adsorption on EZ and FEZ nanoadsorbents.

Temperature (K)	FEZ ΔG° (kJ/mol)	FEZ ΔH° (kJ/mol)	FEZ ΔS° (J/mol K)	EZ ΔG° (kJ/mol)	EZ ΔH° (kJ/mol)	EZ ΔS° (J/mol K)
295.15	−10.50	28.89	154.35	−7.14	24.61	138.32
303.15	−18.83	28.89	154.35	−12.12	24.61	138.32
313.15	−27.15	28.89	154.35	−17.03	24.61	138.32

Source note: Reproduced in editable form from [9], Nanomaterials, https://doi.org/10.3390/nano13182572; CC BY 4.0.

Table 4. Directly reproduced kinetic parameters for nickel adsorption on FEZ and EZ adsorbents.

Adsorbent	Qe,exp (mg/g)	PFO Qe,calc	PFO K1	PFO R2	Pseudo-second-order (PSO) Qe, calc	PSO K2	PSO R2	Ki	C	IPD R2
FEZ	321.1	322.28	0.023	0.9994	321.58	2.781	0.9997	8.0276	33.875	0.9764
EZ	287.9	288.35	0.011	0.9991	287.95	1.924	0.9993	6.2782	21.466	0.9726

Source note: Reproduced in editable form from [9], Nanomaterials, https://doi.org/10.3390/nano13182572; CC BY 4.0. PFO = pseudo-first-order; PSO = pseudo-second-order; IPD = intraparticle diffusion.

Table 5. Directly reproduced comparison of nickel-removal efficiency for eggshell-, zeolite- and FEZ/EZ-related adsorbents.

Adsorbent type	Removal efficiency (%)	Ni initial concentration	Reference in source table
Eggshell	90.9	100 mg/L	[6]
Eggshell	93.5	100 ppm	[7]
Eggshell-derived hydroxyapatite	91.0	100 mg/L	[9]
Vinegar-treated eggshell waste biomass	76.5	1000 ppm	[4]
Clinoptilolite	93.6	100 mg/L	[15]
Zeolite	58.6	1000 mg/L	[3]
Supported zeolite-Y hollow fibre membranes	63.0	10 mg/L	[7]
Clinoptilolite	60.0	25 mg/L	[3]
EZ	97.3	25.5 mg/L	This study
FEZ	99.9	25.5 mg/L	This study

Source note: Reproduced in editable form from [9], Nanomaterials, https://doi.org/10.3390/nano13182572; CC BY 4.0.

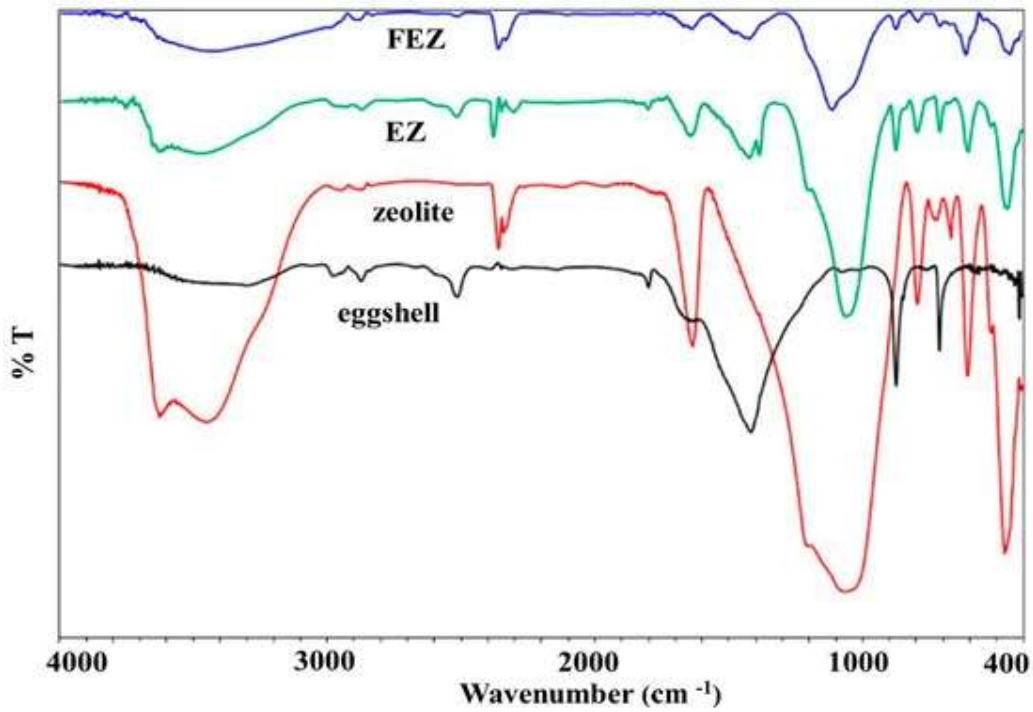

Figure 1. Directly reproduced FT-IR spectra of FEZ, EZ, eggshell and zeolite used to characterise eggshell-waste composite nanoadsorbents. Source: [9], Reproduced from Segneanu et al. [9], *Nanomaterials*, 2023, 13, 2572, https://doi.org/10.3390/nano13182572, under the Creative Commons Attribution 4.0 International License (CC BY 4.0; https://creativecommons.org/licenses/by/4.0/). No changes were made except resizing and formatting.

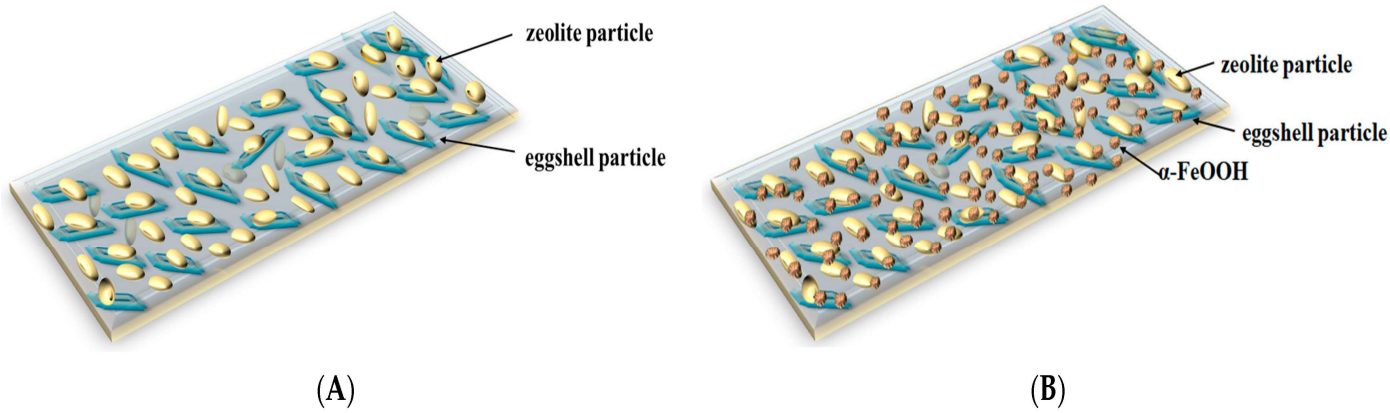

Figure 2. Directly reproduced schematic representation of EZ and FEZ nanoadsorbent structures, showing zeolite, eggshell and alpha-FeOOH distribution. Source: [9], Nanomaterials, https://doi.org/10.3390/nano13182572. Reproduced from an MDPI open-access article under CC BY 4.0.

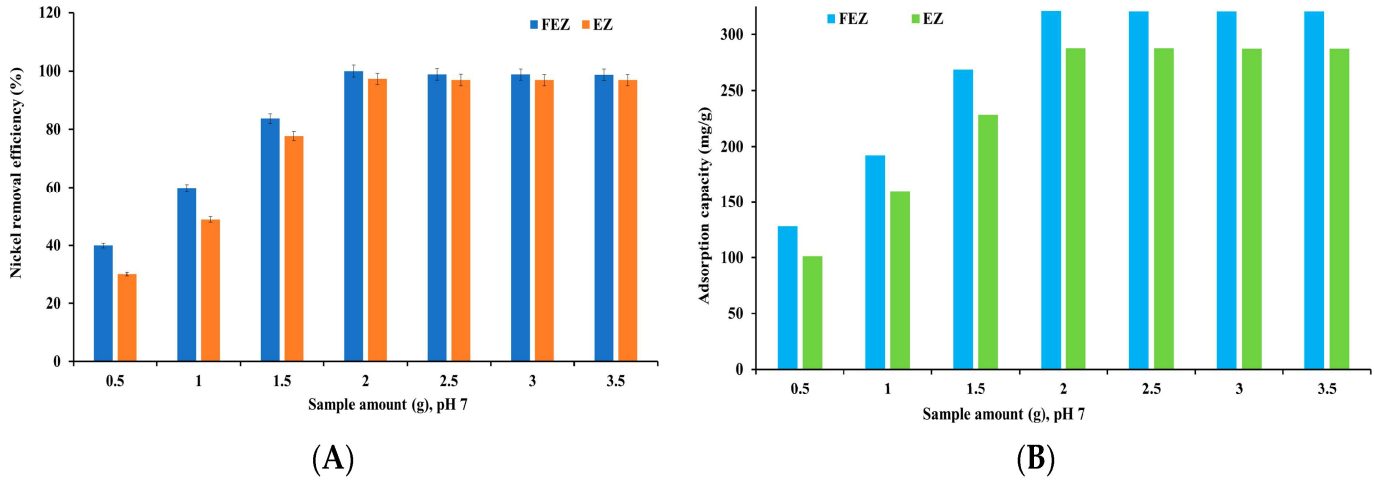

Figure 3. Directly reproduced nickel removal efficiency and adsorption capacity as a function of adsorbent mass for FEZ and EZ. Source: [9], Nanomaterials, https://doi.org/10.3390/nano13182572. Reproduced from an MDPI open-access article under CC BY 4.0.

3.3. Chitosan-carbon dot membranes: Rapid Cd^{2+} removal and light-assisted adsorption

Chitosan-carbon dot hybrid membranes are another instructive waste-compatible platform because they unite a biopolymer matrix with doped carbon-dot functionality. Jlassi et al. (2020) [25] reported an environmentally friendly polymer-carbon dot hybrid film for cadmium removal, where the hybrid membranes achieved rapid extraction and the adsorption followed pseudo-second-order kinetics and Langmuir isotherm behavior.

The reported maximum adsorption capacity was 112.4 mg/g at 25 °C and pH 8, and the hybrid Chitosan-Cyclodextrin membrane reached approximately 93% cadmium removal under UV illumination. The same article reported selectivity patterns of approximately 93% for Cd^{2+}, 55% for Zn^{2+} and 40% for Pb^{2+}, indicating that heteroatom-doped carbon dots embedded in chitosan can modulate metal preference through soft-acid/soft-base interactions and ion exchange [26].

This evidence is important for waste-derived nanoadsorbent design because it highlights a useful principle: nanoscale functionality does not need to be deployed as a free colloidal particle. Embedding functional carbon dots inside a recoverable biopolymer film improves handling, reduces dispersion risk and makes the material more compatible with membrane or fixed-bed remediation designs (**Figures 4 and 5**).

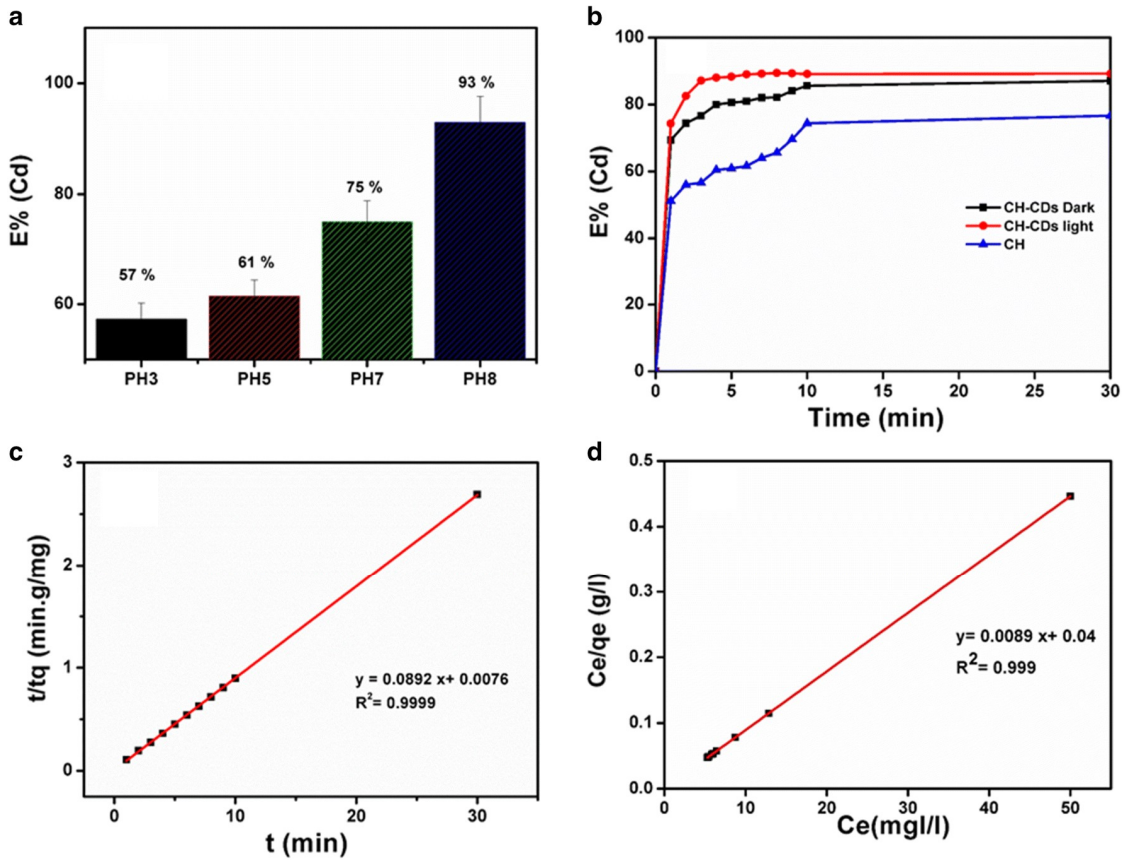

Figure 4. Directly reproduced cadmium extraction efficiency, kinetic fitting and Langmuir fitting for a chitosan-carbon dot hybrid membrane. Source: [11], Environmental Sciences Europe, https://doi.org/10.1186/s12302-020-0292-z Reproduced from a Springer Nature open-access article.

3.4. Cellulose nanomaterials and macroscale usability

Cellulose nanomaterials are especially relevant to water remediation because they combine nanoscale interfaces with macroscale processability. Nanocellulose can be fabricated into membranes, aerogels, sponges, hydrogels and microspheres, enabling the adsorption of dyes, Cr species and oily phases while avoiding some recovery challenges associated with freely suspended nanoparticles [27].

A review by Yang et al. (2025) [10] emphasized that nanocellulose-based recombinant materials can be tailored by filtration, sol-gel, and electrospinning routes. In a waste-to-nano context, this allows lignocellulosic residues to be upgraded into structured sorbents that bridge molecular-scale binding with module-scale water-treatment engineering.

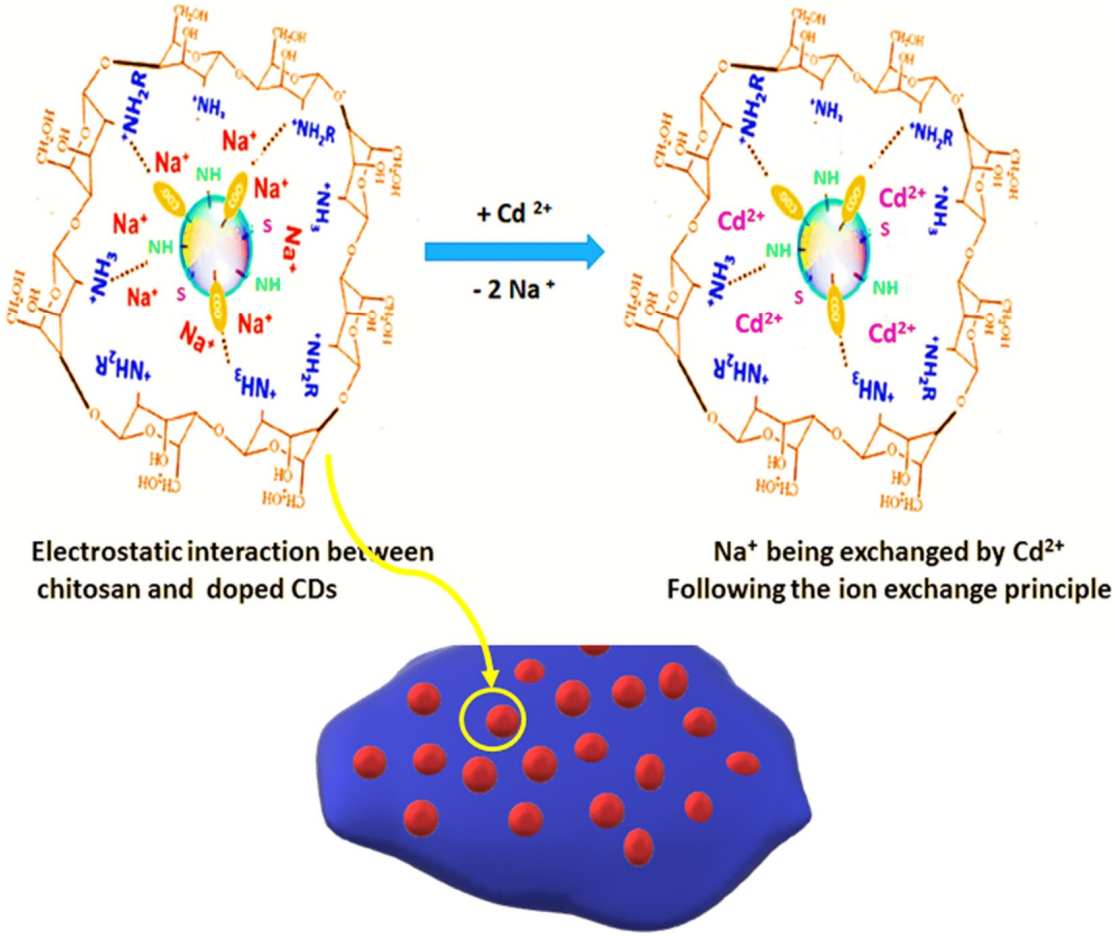

Figure 5. Directly reproduced schematic of the CH-CD membrane and the proposed cation-exchange mechanism during Cd2+ uptake. Source: [11], Environmental Sciences Europe, https://doi.org/10.1186/s12302-020-0292-z Reproduced from a Springer Nature open-access article.

A central limitation of cellulose nanomaterials is that native hydroxyl-rich surfaces may require functionalization to raise affinity for specific anions, cations or hydrophobic dyes. Therefore, practical cellulose-based remediation increasingly relies on hybridization with magnetic particles, amine groups, metal oxides, and graphene oxide or biochar-type components to increase selectivity and facilitate regeneration [7].

3.5. Magnetic nanocomposite adsorbents and regeneration

Magnetic nanoadsorbents offer a practical separation advantage because they can be recovered using external magnetic fields, reducing the difficulty of post-treatment solid-liquid separation. Recent reviews emphasize that magnetic composites are attractive for heavy metals, dyes and pharmaceuticals, but also warn that regeneration losses, aggregation, fouling and incomplete life-cycle assessment limit claims of sustainability.

From a circular-economy perspective, magnetic recovery is useful only when the adsorbent retains capacity after repeated cycles. Reports on regeneration and recyclability show that capacity loss across cycles is a major operational determinant; therefore, future studies should report at least five adsorption-desorption cycles,

magnetic recovery efficiency, leached iron, target-contaminant mass balance and residual toxicity of treated water.

Magnetic biochar is particularly aligned with the announced special issue because it can be produced from crop residues or other biomass and modified with iron phases to combine porosity, redox activity and field-assisted recovery. Scientometric evidence places magnetic biochar as the largest keyword cluster in the biochar adsorption literature, reinforcing its status as a central platform rather than a marginal modification [12].

3.6. Contaminant-specific performance: heavy metals, dyes, antibiotics, per- and polyfluoroalkyl substances (PFAS) and microplastics

Heavy-metal uptake is the most mature application area for waste-derived nanoadsorbents because metal adsorption can be quantified by equilibrium capacity, kinetic constants, pH response and regeneration/desorption efficiency. The strongest case studies show that surface functional groups, metal oxides, carbonate phases and heteroatom-doped carbon domains can coordinate or exchange metal ions under controlled pH conditions [28].

Dye adsorption is often used as a model for organic pollutants because molecules such as methylene blue, safranin and rhodamine B respond to electrostatic attraction, pi-pi interactions, pore filling and photocatalytic degradation. The dye performance should not be overgeneralized to real industrial wastewater, where salts, natural organic matter and mixed contaminants can reduce apparent adsorption capacity [29].

Antibiotics and antibiotic resistance genes introduce a more demanding remediation problem because adsorption must be distinguished from degradation or biological inactivation. Springer's Bio Resources and Bioprocessing study on copper oxide nanoparticles and nano-zero-valent iron for levofloxacin removal illustrates how nanoadsorbent systems can interact with antimicrobial residues, but risk assessment must also examine transformation products and microbial selection pressure [30].

Per- and polyfluoroalkyl substances (PFAS)-related adsorption has shifted attention towards materials with tunable hydrophobic, electrostatic and fluorophilic domains. Metal-organic framework MOF-based and carbonaceous nanoadsorbents are frequently discussed, but their field deployment depends on regeneration without secondary release of persistent fluorinated contaminants and on safe management of spent adsorbents [30].

Microplastic adsorption/removal by nanomaterials is still an emerging area. Recent reviews identify magnetic, carbon-based, biochar-related and metal-oxide nanomaterials as potential microplastic removal tools, but the field requires standardized microplastic size distributions, polymer types, aging status, co-contaminant scenarios and ecological safety tests before practical claims can be accepted [31].

3.7. Mechanisms of adsorption and remediation

Mechanistic interpretation is strongest when surface characterization before and after adsorption is combined with kinetic and isotherm modelling. The main mechanisms include electrostatic attraction, ion exchange, inner-sphere complexation, precipitation, pore filling, hydrogen bonding, pi-pi interactions, redox transformation and photocatalytic degradation, depending on the target pollutant and adsorbent surface chemistry [9].

Langmuir and Freundlich models are widely used, but they must not be treated as definitive proof of monolayer or multilayer adsorption without complementary evidence. Similarly, pseudo-second-order fitting is compatible with chemisorption-like behavior but does not alone identify the chemical bond or rate-limiting step; it should be interpreted with Fourier-transform infrared spectroscopy (FT-IR) shifts, X-ray Photoelectron Spectroscopy (XPS data), Scanning electron microscopy (SEM)/ Energy-Dispersive X-ray Spectroscopy EDX mapping, zeta potential and desorption behavior [32].

The most compelling studies move beyond performance percentages and quantify adsorption capacity, energy or chemical inputs, regeneration yield, stability and potential secondary contamination. This broader evidence structure is necessary because a nanoadsorbent with high single-use capacity may still be environmentally weak if it requires toxic synthesis, releases nanoparticles, loses function after one cycle or generates a hazardous spent material (**Table 6**) [8].

Table 6. Adsorption mechanisms and confirmatory evidence recommended for waste-derived nanoadsorbent studies.

Mechanism	Typical contaminants	Material features that support the mechanism	Evidence needed for rigorous interpretation	References
Ion exchange	$^{+}Cd^{2}$, $^{+}Pb^{2}$, $^{+}Ni^{2}$, ammonium	Exchangeable Na^{+}, $^{+}Ca^{2}$, protonated/deprotonated functional sites	pH dependence, released-ion mass balance, post-adsorption elemental mapping	[1]
Surface complexation	$^{+}Ni^{2}$, $^{+}Cd^{2}$, Cr species	Amine, carboxyl, hydroxyl, phosphate, sulphur/nitrogen dopant sites	FT-IR/XPS shifts, kinetic fitting, competitive ion tests	[7]
Electrostatic attraction	Dyes, charged metals, some antibiotics	Zeta potential opposite to contaminant charge, pH-tunable surface charge	pH edge, ionic strength effect, charge reversal analysis	[9]
Pore filling	Dyes, phenols, hydrophobic organics	Hierarchical micro/mesoporosity and high BET surface area	BET/pore-size distribution before and after loading	[10]
Redox/precipitation	Cr(VI), arsenic, phosphate, metal ions	Iron oxides, Nanoscale zero-valent iron (nZVI), alkaline carbonate phases	Speciation analysis, precipitate identification, electron-transfer evidence	[11]
Photocatalytic or photo-assisted removal	Dyes, antibiotics, selected metals	Carbon dots, TiO2, ZnO, photoactive hybrids	Light/dark controls, radical quenching, by-product monitoring	[13]

3.8. Green synthesis routes and process intensification

Hydrothermal carbonization, pyrolysis, activation, precipitation, sol-gel conversion, green extraction, biopolymer casting, and low-temperature mineral functionalization are the dominant routes for converting waste into adsorption-active nanomaterials. The route should be selected based on precursor chemistry: lignocellulosic residues are well suited to carbonization and activation; eggshells are suited to carbonate- and calcium-rich composites; chitosan matrices are suited to

membrane casting and metal-chelation platforms; and mineral residues such as fly ash can be converted into geopolymeric adsorbents [33].

A critical distinction must be made between green synthesis and merely low-cost synthesis. Green synthesis requires attention to solvent toxicity, energy demand, acid/base consumption, washing burden, yield, waste liquor and post-treatment of the spent adsorbent. Many reports describe waste-derived precursors, but the overall synthesis may still be environmentally intensive if it depends on strong oxidants, excessive acids or high-temperature activation without energy recovery [34].

Process intensification should prioritize synthesis steps that simultaneously generate surface area, introduce binding groups and stabilize the adsorbent structure. For instance, iron-functionalization can enhance magnetic recovery and provide additional sorption sites, while biopolymer immobilization can suppress nanoparticle release and improve reusability. However, multifunctionality should be justified by improved performance or operational simplicity, not merely by adding complexity to the material.

The reviewed literature indicates that the most mature waste-to-nano designs are not necessarily the most compositionally exotic; rather, they are the materials in which precursor choice, synthesis method, characterisation and adsorption testing are internally coherent. The eggshell-zeolite-iron nanoadsorbent study is a good example because the synthesis is explicitly connected to nickel removal, isotherm fitting, kinetic interpretation, thermodynamic feasibility and regeneration [35].

Scale-up readiness requires synthesis workflows that can tolerate feedstock variability. Agricultural residues, eggshell waste, seafood-derived chitosan, fly ash and other mineral wastes differ by geography, season, processing history and contamination profile. A reliable waste-to-nano platform must therefore include feedstock pre-characterization, batch-to-batch quality control and acceptance criteria for ash, moisture, carbon, mineral composition and toxic impurities [36].

3.9. Characterization hierarchy for publishable waste-derived nanoadsorbents

A high-quality manuscript on waste-derived nanoadsorbents should not report adsorption capacity without a characterization hierarchy. At minimum, morphological evidence, crystalline or amorphous phase evidence, surface-functional evidence and porosity evidence should be connected to the observed adsorption behavior. Scanning electron microscopy (SEM) or TEM can reveal morphology, X-ray diffraction (XRD) can identify crystalline phases, Fourier-transform infrared spectroscopy (FT-IR) can identify functional groups, Brunauer-Emmett-Teller surface-area analysis (BET) can quantify accessible surface area, and zeta-potential analysis can indicate pH-dependent electrostatic interaction [9].

Fourier-transform infrared spectroscopy (FT-IR) is especially important for waste-derived systems because precursor-based functional groups often drive adsorption. Shifts or intensity changes in hydroxyl, carboxyl, amine, phosphate, carbonate and metal-oxygen bands before and after pollutant uptake can support hypotheses of complexation, ion exchange or hydrogen bonding. Fourier-transform infrared spectroscopy (FT-IR) alone is insufficient for mechanistic proof because

overlapping bands in heterogeneous waste-derived materials can obscure specific binding events [11].

Scanning electron microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy EDX are valuable for demonstrating particle morphology and elemental distribution, but they should be interpreted cautiously. A high-resolution micrograph can confirm pore development or composite distribution, while Energy-Dispersive X-ray Spectroscopy EDX after adsorption can show the presence of nickel, cadmium or chromium on the adsorbent. Nevertheless, surface mapping does not quantify binding strength or adsorption reversibility and must be paired with desorption, mass balance and kinetic data [37].

Brunauer-Emmett-Teller surface-area analysis (BET) surface area is often treated as the dominant predictor of adsorption, yet many waste-derived nanoadsorbents depend more on chemical functionality than total area. A material with moderate surface area but abundant amine or carbonate sites may outperform a high-area carbon for certain metal ions. The stronger review position is therefore that porosity, chemistry and contaminant speciation act together, and no single characterization metric should be used as a universal performance predictor [38].

For direct journal submission, the characterization section should be linked to the results section rather than presented as a disconnected list of techniques. Each technique should answer a specific question: whether the waste conversion occurred, whether Nano-structuring was achieved, whether active functional sites exist, whether pollutant uptake modifies those sites, and whether the adsorbent remains structurally stable after regeneration [38].

3.10. Adsorption models, kinetics and interpretive limits

Adsorption isotherms are necessary for comparing materials, but they are often overinterpreted. Langmuir fitting is frequently described as monolayer adsorption on homogeneous sites, whereas Freundlich fitting is associated with heterogeneous multilayer adsorption. In real waste-derived nanoadsorbents, surfaces are usually heterogeneous, and model selection should be supported by physicochemical evidence rather than by R2 values alone.

The nickel-removal data support a balanced interpretation. Both Langmuir and Freundlich models provided strong fits, but the higher Freundlich R2 values and the heterogeneous composite architecture supported a multilayer or heterogeneous adsorption interpretation. The agreement between experimental and calculated Qe values strengthened the reliability of the adsorption capacity data [9].

Kinetic models should also be used carefully. Pseudo-first-order and pseudo-second-order equations provide useful descriptive parameters, but they do not alone prove physical or chemical adsorption. The pseudo-second-order model is often consistent with chemisorption contributions, yet chemical interaction should be substantiated by post-adsorption Fourier-transform infrared spectroscopy (FT-IR), X-ray Photoelectron Spectroscopy (XPS), Energy-Dispersive X-ray Spectroscopy (EDX), pH response or desorption evidence [39].

Intraparticle diffusion modelling is useful when porous adsorbents are evaluated, because pollutant uptake may involve boundary-layer diffusion, pore diffusion and

surface reaction steps. If the intraparticle diffusion plot does not pass through the origin, then intraparticle diffusion cannot be the sole rate-limiting step. This type of interpretation is particularly important for biochar, nanocellulose aerogels and mineral-carbon hybrid adsorbents [12].

Future journal papers should report raw adsorption conditions alongside fitted parameters: pH, ionic strength, temperature, initial concentration, adsorbent dose, contact time, particle size, mixing rate and matrix composition. Without these details, high-capacity values cannot be compared fairly, and the field becomes vulnerable to exaggerated claims that are not reproducible in real water [40].

3.11. Regeneration, reuse and spent-adsorbent management

Regeneration converts adsorption from a single-use laboratory result into a potentially deployable remediation technology. Acid, base, salt, solvent, thermal and electrochemical regeneration routes can recover active sites, but they also create secondary streams that must be managed. Therefore, regeneration should be assessed by recovery percentage, adsorption capacity retention, number of cycles, chemical consumption and residual toxicity.

Acid desorption is common for metal-laden adsorbents because protons can compete with metal ions for binding sites; high nickel desorption was achieved using nitric acid, and strong adsorption was maintained after multiple cycles. Such results indicate practical promise, but a complete circularity analysis would also consider the recovery or reuse of the desorbed nickel-containing solution, corrosion risk, acid neutralization and spent-material valorization [41].

Magnetic adsorbents simplify solid-liquid separation, but magnetic recovery does not guarantee regeneration. Aggregation, oxidation, loss of magnetic response, fouling and iron leaching can reduce multicycle value. Reviews of magnetic nanomaterials consistently indicate that the field needs stronger standards for reuse testing and environmental safety, especially if materials are intended for natural waters rather than controlled synthetic solutions [7].

Membrane and film adsorbents, such as chitosan-carbon dot composites, may offer stronger operational control because the nanoscale active phase is immobilized within a recoverable matrix. This can reduce concerns about nanoparticle release and make the system more compatible with module-scale engineering. However, membrane fouling, mechanical durability and regeneration-induced swelling must be tested before field claims are made [10].

Spent adsorbents should be viewed as secondary resources rather than unavoidable waste whenever possible. Metal-loaded adsorbents may be regenerated for metal recovery, immobilized into construction materials, transformed into catalysts or stabilized for safe disposal. The best endpoint depends on pollutant toxicity, adsorbent composition and local regulations, but it should be described explicitly in high-quality review and research manuscripts [42].

3.12. Techno-economic and life-cycle dimensions

A material is not sustainable simply because its precursor is a waste. The total sustainability profile depends on collection, washing, drying, grinding, chemical

activation, heat treatment, solvent use, yield, adsorbent dose, regeneration, lifetime and disposal. Life-cycle assessment should therefore be integrated early rather than added after performance claims have already been made [43].

Techno-economic analysis is especially important for low-cost nanoadsorbents because the precursor may be inexpensive while processing is costly. High-temperature activation, freeze-drying, nanostructure templating, repeated washing, and reagent-intensive functionalization can dominate costs. Therefore, the economically credible route is not always the one with the highest adsorption capacity; it is the one with acceptable capacity, a low synthesis burden and robust reuse [43].

Scale-up also requires consistent feedstock supply. Eggshell waste, rice husk, coconut biomass, crop residue and fly ash may be abundant in some regions but not universally available. Region-specific waste streams should be matched with region-specific pollutant priorities, such as heavy metals near mining areas, dyes near textile clusters, antibiotics near pharmaceutical discharge zones or nutrient pollutants near agricultural runoff areas [12].

A strong future manuscript in this special issue could include a techno-economic comparison between conventional activated carbon and waste-derived nanoadsorbents under identical removal targets. Such a comparison should include synthesis cost, adsorption capacity, required dose, regeneration cost, cycle life, sludge or secondary waste, and treated-water quality. This would help move the field from promising materials to deployable technologies [1].

Environmental risk assessment should include nanoparticle leaching, transformation under pH and redox gradients, ecotoxicity, microbial effects, and behavior of spent adsorbents. This is critical because nanomaterials deployed for remediation can become secondary contaminants if they are not immobilized, recovered or safely integrated into engineered treatment units [20].

3.13. Future research roadmap from laboratory adsorption to deployable remediation

First, waste-derived nanoadsorbent studies should adopt common benchmarking contaminants and conditions. For metals, this could include $^{+}Ni^{2}$, $^{+}Cd^{2}$, $^{+}Pb^{2}$ and Cr(VI) at defined pH and ionic strength; for organics, methylene blue or tetracycline can be used as model compounds but should be followed by real wastewater validation. Standardization would improve cross-study comparability and reduce overstatement [12].

Second, mixed-contaminant experiments should become routine. Real wastewater rarely contains a single pollutant, and competing ions or organic matter can suppress adsorption. Nanoadsorbents that perform well in ultrapure water may fail in municipal, textile, tannery or industrial effluents. Studies should therefore include synthetic and real matrices as separate performance tiers [10].

Third, safety and release testing should be integrated with performance evaluation. Materials such as carbon dots, iron oxides, graphene oxide and nanoscale zero-valent iron can be useful, but environmental release, oxidative transformation and ecotoxicity must be evaluated. Immobilized formats, magnetic recovery and

monolithic composites may reduce these risks if they remain stable during operation [20].

Fourth, pilot-scale design should focus on unit integration. Waste-derived nanoadsorbents can be used in packed columns, membrane modules, magnetic separation units, hybrid adsorption-photocatalysis systems or polishing stages after biological treatment. The best configuration depends on pollutant concentration, hydraulic residence time, fouling profile and regeneration method [7].

Fifth, journal submissions should include a translational limitations paragraph. A high-quality review should not claim that all waste-derived nanomaterials are immediately deployable. It should identify which materials have only proof-of-concept evidence, which have multicycle regeneration, which have real wastewater tests and which could plausibly enter pilot-scale validation [8].

3.14. Pollutant-by-pollutant evidence interpretation for priority remediation targets

Nickel, cadmium, lead and chromium remain the most frequently used metal models because their aqueous behavior is sensitive to pH, competing ions and adsorbent surface chemistry. The nickel data from eggshell-zeolite-iron nanoadsorbents and the cadmium data from chitosan-carbon dot membranes demonstrate that high-capacity metal removal is most credible when pH, kinetics, isotherms, thermodynamics and desorption are reported together [2].

Chromium is mechanistically complex because Cr(VI) and Cr(III) differ in charge, toxicity, mobility and treatability. Cellulose nanomaterials and modified carbonaceous adsorbents can remove chromium through electrostatic attraction, reduction, complexation or precipitation, but studies must clearly specify chromium speciation and analytical method to avoid misleading comparisons [2].

Dye removal remains valuable for adsorption science because cationic and anionic dyes probe electrostatic and aromatic interactions. Dye removal should not be treated as equivalent to removal of real industrial mixtures. Textile wastewater includes salts, surfactants, auxiliaries and multiple dyes, and these matrix effects can alter adsorption kinetics and surface saturation [14].

Antibiotics and pharmaceutical residues require a more cautious framework because apparent removal may involve adsorption, degradation, photolysis or irreversible binding. When nanoadsorbents are used for antibiotics, authors should monitor parent compound disappearance, possible transformation products, residual antibacterial activity and co-selection of resistance genes [18].

Pharmaceutical residues, including antibiotics, analgesics, anti-inflammatory drugs, and hormones, are increasingly detected in surface water and groundwater because conventional wastewater treatment plants do not completely remove them. These contaminants contribute to antimicrobial resistance and may disrupt endocrine systems in aquatic organisms. Research demonstrates that functionalized biochar, activated carbon nanoparticles, and cyclodextrin-based materials effectively adsorb many Pharmaceuticals and Personal Care Products (PPCPs) through hydrophobic interactions, hydrogen bonding, and inclusion complex formation [48].

Per- and polyfluoroalkyl substances (PFAS) adsorbent research is rapidly expanding but remains difficult because short-chain and long-chain per- and polyfluoroalkyl substances (PFAS) have distinct adsorption behavior and regeneration demands. Metal-organic framework (MOF) and carbon-based nanomaterials can offer high affinity, but the decisive questions are whether per- and polyfluoroalkyl substances (PFAS) are irreversibly captured, safely regenerated or destroyed after concentration [3].

Agricultural runoff introduces pesticides such as atrazine, glyphosate, chlorpyrifos, and carbofuran into water bodies. These chemicals are associated with ecological toxicity and potential human health risks. Studies suggest that modified biomass-derived adsorbents, particularly those containing cyclodextrin or activated carbon, provide effective removal through hydrophobic adsorption and host–guest interactions. However, adsorption efficiency depends strongly on the pesticide's chemical structure and solution conditions [42].

Microplastics represent a different contaminant class because removal involves particle capture rather than molecular adsorption alone. Nanomaterials may help through magnetic aggregation, filtration enhancement or surface interaction, but standard tests should define polymer type, particle size, ageing, biofilm formation and co-contaminant loading [20].

Nutrient removal, particularly phosphate and ammonium, should be considered more often in waste-derived nanoadsorbent studies because spent adsorbents may be reused in agriculture if contaminants are safe and nutrients are recoverable. This opens a circular pathway in which remediation is linked to nutrient recycling rather than simple pollutant immobilization [17].

Organic contaminants include phenols, benzene, toluene, xylene, polycyclic aromatic hydrocarbons (PAHs), and petroleum hydrocarbons. These compounds are commonly released from petrochemical, pharmaceutical, and manufacturing industries. Evidence indicates that carbon-rich nano-adsorbents with high surface areas effectively remove these pollutants via hydrophobic interactions, π–π electron interactions, and pore adsorption. Magnetic biochar further facilitates easy recovery of the adsorbent after treatment [41].

Phenols and other industrial organics require careful distinction between adsorption and catalytic degradation. If an adsorbent contains photoactive or redox-active domains, authors should include light/dark controls, radical-scavenging tests and total-organic-carbon measurements to verify mineralization rather than only disappearance from solution [5].

This surface modification strategy provided a rapid and effective route for producing a multifunctional adsorbent with enhanced selectivity toward Cr(VI) oxyanions. The successful fabrication and magnetic characteristics of M-TACA were confirmed through advanced characterization techniques, including scanning electron microscopy (SEM) and vibrating sample magnetometry (VSM).

The adsorption behavior of Cr(VI) was systematically evaluated by examining the effects of important operating parameters, such as solution pH, adsorption time, initial contaminant concentration, and adsorbent dosage. The results demonstrated that the adsorption performance was highly influenced by pH, with the maximum Cr(VI) uptake reaching 117.65 mg g^{-1} at pH 3. In addition, the influence of

coexisting ions, including Cu^{2+}, Zn^{2+}, Ni^{2+}, Cl^{-}, PO_4^{3-}, and SO_4^{2-}, was investigated to assess the practical applicability of M-TACA in complex water matrices. The equilibrium adsorption data showed the best agreement with the Langmuir model, indicating that Cr(VI) adsorption mainly occurred through monolayer interaction with uniformly distributed active sites. Kinetic analysis using the intraparticle diffusion model suggested that the adsorption process involved sequential steps, including rapid surface binding followed by diffusion-controlled adsorption within the material structure. Thermodynamic evaluation revealed that Cr(VI) removal by M-TACA was a spontaneous and exothermic process involving both physical and chemical interactions [43].

3.15. Waste-stream classification and recommended nanomaterial pathways

Agricultural residues such as rice husk, wheat straw, corn stalks, coconut shells, and fruit peels are well suited for producing carbon-rich adsorbents because their lignocellulosic composition can be converted into biochar, activated carbon, carbon dots or nanocellulose. Their advantage is abundance, but their limitation is variability in ash content, mineral impurities, and seasonal collection logistics [12].

Food-processing residues such as eggshells and shells from animal-origin wastes provide inorganic or biopolymeric platforms. Eggshells can contribute calcium carbonate and porous mineral structures, while seafood-derived chitosan offers amine-rich binding capacity. These residues are attractive because they already contain chemically useful frameworks for metal ion uptake [11].

Industrial mineral wastes such as fly ash and alumino-silicate residues can be converted into geopolymers or zeolite adsorbents. Their strength lies in inorganic stability and ion-exchange capacity, but careful screening for hazardous elements is necessary before they are marketed as green materials [17].

Plastic and polymer wastes are increasingly discussed as nanomaterial precursors, but their environmental advantage is not automatic. Conversion into carbonaceous nanomaterials may require high energy and strict emission control; therefore, plastic-derived nanoadsorbents should include thermal input, gaseous emissions, and additive residues in their sustainability evaluation [22].

Electronic and metal-rich wastes can provide valuable elements for oxide or magnetic nanomaterials, but they also carry high toxicity risk. For such feedstocks, hydrometallurgical recovery, purification, life-cycle assessment and leaching tests are essential before environmental-remediation claims can be made [1].

Municipal organic waste and sewage sludge can be converted into biochar-like adsorbents, yet regulatory barriers are stronger because of pathogens, pharmaceuticals, microplastics and heavy metals. The most defensible use of such feedstocks is in controlled applications where contaminant release is evaluated and the spent material is safely managed.

The waste-stream pathway should be chosen according to regional availability and pollutant need. A country or province with abundant eggshell waste and metal-contaminated water may rationally prioritize mineral-bio-waste composites, whereas

rice-producing regions may prioritize silica-rich rice husk ash or biochar derivatives [12].

The most advanced review contribution is therefore a decision framework: carbon-rich residues for hydrophobic organics and dyes, carbonate/mineral residues for metal ions, chitosan/cellulose residues for chelation and membranes, iron-bearing routes for magnetic recovery, and geopolymer routes for robust mineral immobilization [16].

3.16. Field-readiness, pilot testing and realistic-water validation

The majority of nanoadsorbent studies remain laboratory-scale tests in synthetic single-contaminant solutions. While such tests are useful for mechanistic screening, they do not capture the complexity of real wastewater, where pH fluctuations, dissolved organic matter, competing ions, suspended solids and microbial communities can substantially change adsorption behavior [21].

Realistic-water validation should progress in tiers. Tier 1 uses single-contaminant ultrapure water to determine mechanism; Tier 2 uses simulated multi-ion water to test competition; Tier 3 uses real wastewater or surface water; and Tier 4 uses continuous-flow columns or membrane modules. Each tier should include mass balance and regeneration assessment [2].

Column studies are particularly important because batch adsorption can overestimate practical performance. In fixed-bed mode, breakthrough curves, empty-bed contact time, hydraulic resistance and fouling determine whether the material can operate in treatment systems. Nanocellulose membranes and immobilized chitosan-carbon dot films may be more scalable than dispersible powders if mechanical strength is sufficient [10].

Powdered nanoadsorbents require a separation step after adsorption. Magnetic modification, membrane immobilization, granulation, palletization or composite incorporation can reduce recovery problems, but each modification may lower accessible surface area or add cost. Therefore, processability should be considered part of performance, not an optional engineering afterthought [8].

Pilot-scale testing should report not only pollutant removal but also pressure drop, flow stability, head loss, fouling, regeneration time, chemical consumption, and sludge generation. These metrics determine whether a material with excellent laboratory capacity can withstand realistic operational constraints.

Field-ready systems must also meet regulatory and social acceptability criteria. Waste-derived materials intended for drinking-water or agricultural-water applications require strong evidence of non-toxicity, low leaching, and reliable removal under variable conditions. Public acceptance may be higher when the material is immobilized and recoverable rather than released as dispersed nanoparticles [20].

In low-resource settings, the most valuable technologies are those that are locally manufacturable, reusable, easy to regenerate and not dependent on costly instruments. Eggshell-based composites, biochar-derived adsorbents and cellulose/chitosan membranes may therefore be more relevant than highly complex

nanostructures if they deliver adequate performance with accessible production infrastructure [9].

The present manuscript is positioned to help bridge the laboratory-field gap by presenting source-traceable figures and tables, extracting actual adsorption values, and emphasizing regeneration, process ability and life-cycle logic. This is aligned with the special issue's aim to link waste valorization with application-driven environmental remediation.

3.17. Practical recommendations

A waste-precursor description table should be included as a future study element providing the source, pre-treatment, moisture content, ash content, mineral composition and potential contaminants. This is required due to the fact that one of the most significant issues for reproducible synthesis of Nano adsorbents is the variability in waste precursors [12].

The yield of synthesis, mass balance of reagents and washing procedure should be reported by the authors. The environmentally preferable nature of a material may not be warranted even if the starting precursor is inexpensive or waste derived and is used in large amounts of acid, base, or solvent. [22]

Adsorption tests should include at least one experiment with competing ions and one with real water or a simulated real-water matrix. This would yield more useful reported capacities for environmental remediation and minimize the risk that the reported capacity obscures the fact that the water is idealized laboratory water.

Capacity retention and desorption-stream management should be used to assess regeneration over multiple cycles. Ten or more cycles provide a stronger level of evidence for practical re-use, while 5 cycles represent the minimum required for screening.

Dispersible or weakly immobilized materials should routinely be tested for nanoparticle release. If additional nanoscale contaminants are introduced into the treated water by the remediation process itself, the purpose of water remediation is defeated [20].

The economic evaluation should be based not only on capacity per gram but also on the estimated dose of adsorbent per cubic meter of treated water. This will enable laboratory performance to be translated into the actual cost of treatment and allow comparison with the cost of activated carbon, ion exchange resins, and conventional adsorbents [31].

The most promising future developments are hybrid modular treatment: use of waste products in the form of nanoadsorbents as polishing units after the biological treatment, magnetic separation for recovery of high-value contaminants and immobilized membranes for low release applications. This integration can render the application of nanotechnology more practical than in isolation, powder dosing [7].

Finally, field mapping by readiness level would be helpful in future reviews. Only synthetic-water batch testing should be labeled as materials "proof-of-concept", regeneration and matrix testing as "pre-pilot" and column data, life cycle analysis and toxicity testing as "pilot-ready" [13].

4. Discussion

The waste-based nanoadsorbents are not just simply low-cost replacements for commercial activated carbon. They are being developed into engineered materials with feedstock chemistry, nanoscale architecture, functional surface design and regeneration strategy being the key points that decide the suitability of the adsorbent for real wastewater [30].

It also demonstrates that removal percentage is not an adequate measure of performance ranking. Initial concentration, adsorbent dose, pH, ionic strength and contact time are significant factors that affect the removal efficiency. For instance, in the (Iron-functionalised eggshell-zeolite nanoadsorbent FEZ/Eggshell-zeolite composite nanoadsorbent EZ) study, very good Ni removal results were obtained, but this result is meaningful, since the article also provided isotherm, kinetic, thermodynamic and regeneration data which enable readers to interpret the result mechanistically [29].

Regeneration is a crucial translational parameter. A nanoadsorbent that demonstrates strong academic success but is commercially unsuccessful can be due to an inability to regenerate the material at a lower cost than the cost of the pollutants removed, or because the pollutants are not recovered and a higher-concentration stream of pollutants is generated during the regeneration process. Again, the Iron-functionalised eggshell-zeolite nanoadsorbent FEZ/Eggshell-zeolite composite nanoadsorbent EZ example is more convincing than some laboratory reports, as it reported acid-assisted desorption and multicycle loss, and the literature on magnetic nanoadsorbents indicates that recovery and regeneration are still not surmountable issues in many systems [28].

The second translation problem is how to safely handle nanoscale materials. The use of waste as a feedstock does not necessarily make a nanomaterial sustainable. The lower energy of synthesis, fewer hazardous reagents, low leaching, minimal release of nanoparticles, high regeneration efficiency and an end-of-life path for spent adsorbents are all key features in the sustainability of the process [15].

The field should include standard reporting procedures. Manuscripts should include at least information about precursors, pre-treatment, moisture/ash composition in the case of ashes, synthesis yield, particle size distribution, Brunauer-Emmett-Teller surface-area analysis (BET) surface area, pore-size distribution, Particulate Organic Carbon (POC), Zeta potential, pollutant speciation, competing ions, adsorption capacity, adsorption capacity kinetics, adsorption isotherms, regeneration, leaching and toxicity of treated water. Nanostructured and composite adsorbents exhibit enhanced contaminant removal due to their high surface area, abundant active sites, and tunable surface chemistry. Nevertheless, sustainable production routes remain necessary to overcome limitations related to cost and environmental impact [40]. A lack of such metadata results in poor ability to compare across studies and unreliable scale-up models [27].

Traced back to their source, the figures and tables reproduced in this manuscript make it evident what the importance of source-level traceability is. Eggshell waste provides all the structural, adsorption, kinetic, and thermodynamic data in a single package, whereas the Springer article on chitosan-carbon dot offers mechanistic and kinetic figures that relate surface chemistry with cadmium uptake. These source-

traceable materials provide a stronger base than generic schematic figures as they back up claims with evidence from experiments [28].

Indiscriminate accumulation of citations should be avoided in future reviews and instead, build a matrix of comparability which categorizes an adsorbent by precursor, synthesis chemistry, target contaminant, uptake capacity, regeneration, environmental risk and field readiness. Advanced adsorption technologies are increasingly investigated for water purification because of their ability to remove persistent contaminants. However, practical application requires consideration of adsorption capacity, regeneration ability, material cost, and scalability. This will be particularly relevant for the present special issue, which is conceptualized to connect waste valorization with advanced applications for nanomaterials and not just to gather individual laboratory demonstrations [32,38].

Agricultural residues represent promising low-cost and sustainable precursors for the preparation of functional adsorbents. Conversion of biomass waste into biochar and activated carbon can enhance surface area, porosity, and active functional sites, improving the adsorption of toxic metal ions from contaminated water. Adsorption modelling provides insights into pollutant–adsorbent interactions and helps optimize treatment performance [36].

Bio-derived materials and engineered adsorbents offer a sustainable alternative to conventional treatment materials because they combine pollutant removal efficiency with renewable resource utilization [37].

The development of environmentally friendly adsorbents from renewable resources provides an effective strategy for reducing heavy metal contamination while promoting waste valorization and circular economy principles [39].

5. Conclusions

Nanoadsorbent materials derived from waste offer a promising approach to linking circular waste valorization with water and wastewater remediation. There are strong arguments for engineered systems in which the surface chemistry of the waste precursors is specifically designed to interact with the target contaminant chemistry (through surface functionalization), and the system morphology is controlled at the nanoscale (e.g., membranes, monoliths, magnetic composites, or hybrid porous structures) and can be recovered. The diversity and promise of the field is illustrated by the eggshell-zeolite-iron nanoadsorbents, chitosan-carbon dot membranes, cellulose nanomaterial assemblies and magnetic biochar composites. The next step should focus on standardized adsorption procedures, regeneration/reuse, leaching and ecotoxicity evaluation, pilot-scale testing and life-cycle and techno-economic evaluation. The best contribution to this special issue is a review that is not just a list of materials but a move from synthesis to characterization to adsorption mechanisms to regeneration and scale-up to a clear waste-to-remediation pathway.

Abbreviations

Abbreviation	Definition
BET	Brunauer-Emmett-Teller surface-area analysis
CD	Carbon dot

CH	Chitosan
EZ	Eggshell-zeolite composite nanoadsorbent
FEZ	Iron-functionalised eggshell-zeolite nanoadsorbent
FT-IR	Fourier-transform infrared spectroscopy
IPD	Intraparticle diffusion
MOF	Metal-organic framework
nZVI	Nanoscale zero-valent iron
PFAS	Per- and polyfluoroalkyl substances
PSO	Pseudo-second-order
SEM	Scanning electron microscopy
XRD	X-ray diffraction

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