



A Comprehensive Review on Recent Advances in Chitosan and Graphene Oxide Nanocomposites for Environmental, Biomedical and Smart Material Applications

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ABSTRACT

Chitosan–graphene oxide (CS–GO) nanocomposites combine the biodegradability, biocompatibility, cationic character, and film-forming ability of chitosan with the high surface area, oxygen-rich functionality, mechanical reinforcement, and tunable physicochemical properties of graphene oxide, enabling applications in environmental remediation, biomedical engineering, food packaging, sensing, and smart materials. This review critically examines recent advances in CS–GO preparation, interfacial chemistry, characterization, structure–property relationships, sustainability, scale-up, and application performance, with particular emphasis on chitosan molecular weight and degree of deacetylation, GO oxidation level and loading, dispersion, cross-linking, and processing conditions. Hydrogen bonding, electrostatic attraction, covalent coupling, coordination, and π – π interactions govern CS–GO assembly and strongly influence mechanical, adsorption, biological, barrier, electrical, and multifunctional behavior. Environmental remediation and biomedical applications currently have the strongest evidence base, while emerging uses include microplastic capture, desalination, sensing, supercapacitors, proton-exchange membranes, and hydrogen-generation catalysis. Key challenges include inconsistent characterization, limited real-matrix validation, regeneration cost, nanoparticle migration, long-term toxicity, life-cycle impacts, and scalable green manufacturing. Future translation requires standardized characterization, application-specific safety assessment, real-world validation, life-cycle evaluation, and reproducible large-scale fabrication.

Keywords: Chitosan; Graphene oxide; Nanocomposite; Adsorption; Drug delivery; Wound healing; Tissue engineering; Biosensor; Active packaging; Flexible electronics.

1. INTRODUCTION

The transition from petroleum-derived and persistent materials to renewable multifunctional systems has stimulated extensive research on nanocomposites based on natural polymers. Chitosan (CS), obtained by partial deacetylation of chitin, is particularly attractive because it is biodegradable, biocompatible, film-forming, mucoadhesive, antimicrobial, and chemically modifiable. Chitin is abundant in crustacean processing residues, fungal cell walls, and insect exoskeletons; therefore, chitosan production can also support circular utilization of biological waste. The amino and hydroxyl groups distributed along the chitosan backbone enable protonation, chelation, hydrogen bonding, grafting,

cross-linking, and ionic complexation. These attributes explain its use in water treatment, packaging, agriculture, wound care, drug delivery, and tissue engineering (Khandegar *et al.* 2021; Feng and Wang, 2022; Rinaudo *et al.* 2006; Ramamurthy *et al.* 2025). CS–GO nanocomposites are being investigated as sustainable, multifunctional materials for environmental, biomedical, packaging, sensing, and smart-material applications. Chitosan is renewable, biodegradable, biocompatible, and chemically modifiable, but weak mechanical strength, moisture sensitivity, and limited functional performance restrict its use. GO can mitigate these limitations by adding mechanical reinforcement, adsorption sites, oxygen-containing functional groups, photothermal response, and tunable electrical properties.

Earlier reviews have generally emphasized water purification or biomedical applications, leaving synthesis, interface design, characterization, performance, toxicity, sustainability, and scalability fragmented across disciplines. This review integrates those dimensions and identifies the evidence needed to translate CS–GO materials into environmental, healthcare, packaging, and smart-material technologies. Nevertheless, pristine chitosan has important deficiencies. It exhibits modest mechanical strength, limited thermal stability, pronounced swelling, poor solubility near neutral pH, and possible dissolution in acidic media. Its relatively low specific surface area can restrict adsorption kinetics, while strong intramolecular and intermolecular hydrogen bonding complicates processing. These drawbacks motivate reinforcement or functionalization with high-aspect-ratio nanofillers.

Graphene oxide (GO) is a chemically oxidized derivative of graphene containing hydroxyl and epoxy groups on the basal plane and carboxyl and carbonyl groups primarily at sheet edges. Oxidation disrupts the extended sp^2 network but imparts hydrophilicity, aqueous dispersibility, surface charge, and chemical reactivity. GO retains high aspect ratio, substantial mechanical stiffness, large accessible surface area, and useful optical, electrical, and photothermal behavior. Its oxygenated surface can interact with polymers, metal ions, dyes, drugs, biomolecules, and nanoparticles. However, unsupported GO sheets can aggregate, form stable colloids that are difficult to recover, and display concentration-, size-, oxidation-, and exposure-dependent biological effects (Feng and Wang, 2022; Moradi *et al.* 2021; Chang *et al.* 2011). Combining CS and GO is therefore a complementary materials strategy. Protonated chitosan chains adsorb onto negatively charged GO sheets; amino and hydroxyl groups form hydrogen bonds with GO oxygen functionalities; covalent amidation or imine-forming routes can stabilize the interface; and aromatic cargo can interact with residual graphitic domains by π – π stacking. Chitosan prevents sheet restacking and converts GO into processable films, beads, membranes, hydrogels, aerogels, scaffolds, nanofibers, and particles. GO, in turn, reinforces chitosan and introduces adsorption, barrier, sensing, electrical, and photothermal functions (Moradi *et al.* 2021; Chang *et al.* 2011; Saputra *et al.* 2022; Cobos *et al.* 2017).

This application-oriented review integrates material preparation and characterization with pollutant adsorption, electronic-waste remediation, antimicrobial hybrids, drug delivery, wound healing, bone regeneration, food packaging, sensing, and flexible electronics. It emphasizes how interfacial chemistry and processing determine performance and why laboratory results may not translate directly to industrial or clinical settings. Its distinctive contribution is a cross-domain, translation-focused assessment linking synthesis route,

interface design, characterization depth, quantitative performance, toxicity, sustainability, and industrial feasibility.

2. SCOPE AND REVIEW APPROACH

This narrative review covers foundational literature from 2006 onward and application-focused CS–GO studies published mainly during 2006–September 2026. The final narrative corpus comprises 88 cited sources; 35 core journal articles published through 2025 were retained only for the year-wise distribution analysis. Because the source corpus was assembled for a narrative synthesis rather than through a pre-registered systematic-review protocol, the review should not be interpreted as a systematic review or meta-analysis. Quantitative results are reported only when available in the cited sources and are compared cautiously because compositions, test protocols, and experimental conditions differ.

Literature-selection strategy: Sources were identified through Scopus, Web of Science, Google Scholar, PubMed, ScienceDirect, SpringerLink, ACS Publications, RSC journals, and MDPI. Search combinations paired ‘chitosan’ AND ‘graphene oxide’ with ‘nanocomposite’, ‘membrane’, ‘hydrogel’, ‘scaffold’, ‘adsorption’, ‘heavy metal’, ‘dye removal’, ‘drug delivery’, ‘wound dressing’, ‘food packaging’, ‘biosensor’, ‘flexible electronics’, ‘energy storage’, ‘fuel cell’, ‘microplastics’, ‘toxicity’, ‘biodegradation’, ‘life-cycle assessment’, and ‘green syntheses. Studies were retained when they used chitosan and GO/rGO in the same composite, described synthesis or functionalization, provided characterization evidence, and addressed an environmental, biomedical, packaging, sensing, energy, or smart-material application. Studies using the components separately, lacking material characterization, presenting unsupported non-peer-reviewed claims, duplicating records, or failing to connect the application to CS–GO performance were excluded. The current narrative corpus contains 88 cited sources. Because the original number of database records screened was not prospectively recorded, no PRISMA-style claim of exhaustive global coverage is made.

2.1 Publication Trend, Contemporary Importance of Biodegradable Polymers and Global Market Demand

2.1.1 Year-wise Development of Research on Chitosan–graphene Oxide Materials

Research on chitosan–graphene oxide nanocomposites has expanded from fundamental polymer–nanosheet studies to water purification, drug delivery, wound healing, tissue regeneration, food packaging, sensing, antimicrobial materials, energy storage, and flexible electronics. The year-wise profile

below is based on 35 core journal articles published from 2006 through 2025 within the broader 88-source narrative corpus.

Table 1. Year-wise distribution of the 35 core journal articles used for trend visualization

Publication Year	Number of Articles	Percentage of Reviewed Corpus (%)
2006	1	2.9
2010	1	2.9
2011	2	5.7
2013	1	2.9
2017	6	17.1
2018	2	5.7
2019	2	5.7
2020	7	20.0
2021	5	14.3
2022	2	5.7
2023	2	5.7
2024	1	2.9
2025	3	8.6
Total	35	100

Literature was selected through a narrative search of Scopus, Web of Science, Google Scholar, ScienceDirect, SpringerLink, ACS, RSC, MDPI and PubMed using combinations of ‘chitosan’, ‘graphene oxide’, ‘nanocomposite’, ‘adsorption’, ‘drug delivery’, ‘wound dressing’, ‘food packaging’, ‘biosensor’, ‘flexible electronics’, ‘energy storage’, ‘fuel cell’, ‘emerging contaminants and ‘sustainability’, with emphasis on studies published between 2006 and September 2026.

The 35-article distribution was compiled from the core journal studies used for trend visualization and is intentionally retained as a fixed descriptive subset so that the trend figure remains internally consistent. The broader narrative search covers foundational literature from 2006 onward and application-focused literature through September 2026.

Approximately 62.9% of the reviewed articles were published during 2017–2021, confirming that this period represented a major expansion phase for CS–GO research. Studies during this period moved beyond basic film formation and mechanical reinforcement toward magnetic adsorbents, biomedical scaffolds, wound dressings, biosensors, drug-delivery vehicles, and antimicrobial composites. Articles published from 2022 to 2025 increasingly emphasized multifunctional systems, simulated electronic-waste remediation, molecular modelling, recoverability, green synthesis, and application-specific safety.

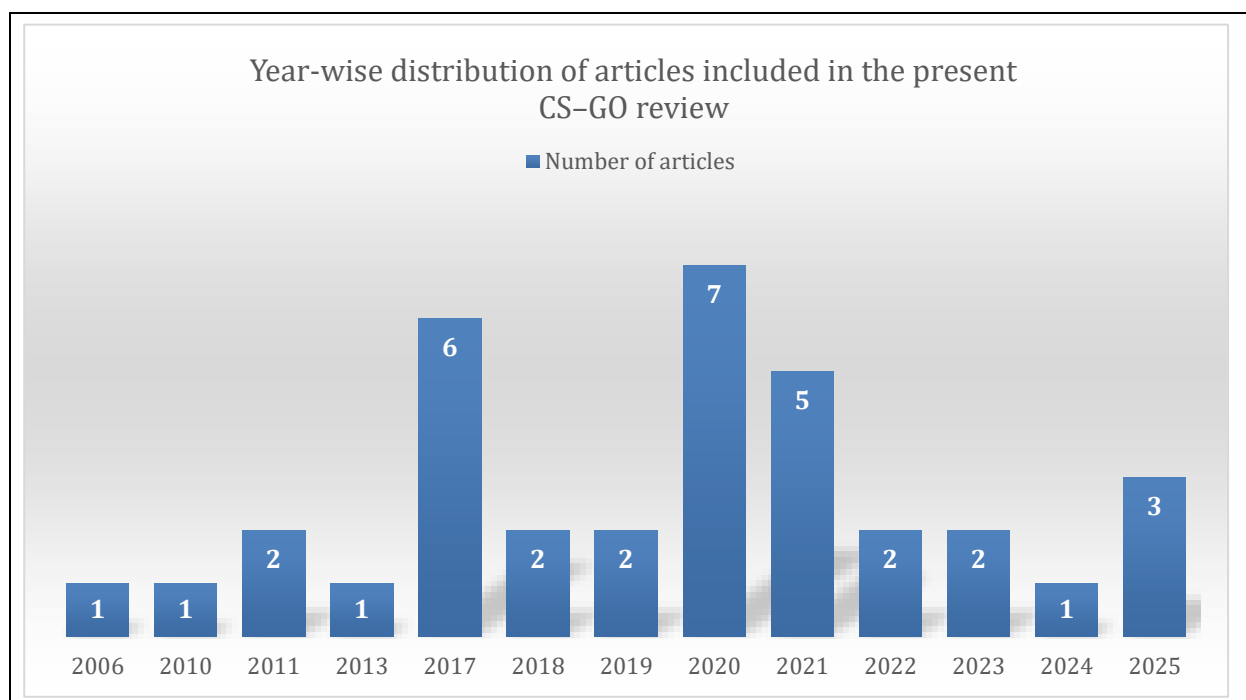


Fig. 1: Year-wise distribution of the 35 core journal articles used for trend visualization

The publication-trend data should be read only as a profile of the 35 references selected for this review. It is not presented as a global bibliometric trend. A complete global mapping would require database-level extraction from Scopus or Web of Science, duplicate removal, document-type filtering, citation normalization and keyword co-occurrence analysis.

Recent literature shows a transition from binary CS–GO composites to ternary and quaternary systems containing Fe_3O_4 , CuFe_2O_4 , Ag, ZnO, TiO_2 , natural extracts, therapeutic molecules, or biological recognition elements. This progression reflects a shift from reinforcement studies toward multifunctional, application-integrated systems. The year-wise values in Table 1 describe only the 35 core journal articles selected for trend visualization and are not a complete global bibliometric record. A formal bibliometric analysis would require a reproducible database search, duplicate removal, and predefined document-type, language, and indexing-date criteria.

2.1.2 Contemporary Importance of Biodegradable Polymers

The increasing interest in biodegradable polymers is closely connected to the environmental persistence of petroleum-derived plastics, the accumulation of packaging waste, the formation of microplastics, and the limited effectiveness of conventional end-of-life practices. Global plastic production, consumption, and waste generation are expected to continue increasing substantially unless stronger policy and material-transition measures are implemented (Yan *et al.* 2024). Consequently, research has intensified on renewable and biodegradable matrices that can provide the functional performance of conventional polymers while reducing dependence on fossil carbon and enabling biologically assisted end-of-life pathways.

Biodegradable polymers are materials whose macromolecular chains can be converted by microorganisms and their enzymes into lower-molecular-weight products and, under appropriate conditions, ultimately into carbon dioxide, water, methane, mineral products, and biomass. However, biodegradation is not an intrinsic yes-or-no property. It depends on polymer structure, crystallinity, molecular weight, thickness, additives, temperature, moisture, oxygen availability, microbial population, and the receiving environment. A material that biodegrades under controlled industrial composting conditions may remain stable for a much longer period in soil, freshwater, marine water, or landfill conditions. Therefore, the terms biodegradable, industrially compostable, home compostable, and bio-based should not be used interchangeably (Yan *et al.* 2024; De Jong *et al.* 2025; Kress *et al.* 2026; Song *et al.* 2009; Barrowclough and Birkbeck, 2022).

The growing importance of biodegradable polymers arises from several complementary advantages. Natural polymers such as chitosan, cellulose, starch, alginate, proteins, and microbial polyesters can reduce dependence on fossil resources because they are derived from renewable biomass, industrial by-products, or biological waste streams. Chitosan is particularly relevant to circular utilization because crustacean-shell, fungal, or insect-derived chitin can be converted into higher-value products such as films, coatings, membranes, adsorbents, scaffolds, and delivery systems. Properly designed biodegradable polymers can also reduce the long-term accumulation associated with persistent petroleum-based materials, especially in applications where collection or mechanical recycling is difficult. Their controlled biodegradation is especially valuable in biomedical applications, including wound dressings, drug-delivery carriers, tissue-engineering scaffolds, temporary implants, and resorbable devices, where the material can gradually degrade or be replaced by biological tissue after fulfilling its intended function. In packaging applications, biopolymers can be combined with antimicrobial agents, antioxidants, nanofillers, freshness indicators, and barrier modifiers to create active and intelligent packaging systems that provide functions beyond passive containment. Biodegradable matrices are also promising for environmental remediation because they can immobilize nanosheets and nanoparticles within recoverable forms such as membranes, beads, hydrogels, and aerogels, thereby reducing the direct release of free nanomaterials. In addition, many biopolymers are compatible with relatively mild processing methods, including aqueous casting, ionic gelation, freeze-drying, electrospinning, and mild cross-linking, although the associated energy demand and chemical consumption should still be carefully evaluated.

Chitosan is particularly important because it combines biodegradability with cationic charge, film-forming ability, antimicrobial activity, mucoadhesion, metal-ion coordination, and chemical modifiability. Nevertheless, its poor moisture resistance, limited mechanical strength, acid solubility, and low electrical conductivity restrict several practical applications. Incorporation of graphene oxide can improve strength, stiffness, barrier behaviour, adsorption capacity, surface functionality, photothermal response, and sensing characteristics. The CS–GO system therefore illustrates how a biodegradable polymer can be functionally upgraded by a nanoscale reinforcement.

It is important, however, to avoid describing every CS–GO composite as completely biodegradable. Chitosan is biodegradable, whereas the environmental degradation and long-term fate of graphene oxide depend on oxidation state, sheet size, concentration, surface functionalization, microbial activity, and exposure conditions. Increasing GO loading or introducing

persistent metallic and metal-oxide nanoparticles may alter disintegration, mineralization, toxicity, and residue formation. Claims of biodegradability should therefore be supported by standardized mass-loss, molecular-weight reduction, carbon-evolution, ecotoxicity, and residual-nanomaterial analyses.

2.1.3 Global Demand for Biodegradable and Bio-based Polymer Materials

The global demand for bio-based and biodegradable polymer materials is increasing because of regulatory restrictions on selected single-use plastics, corporate sustainability commitments, advances in polymer performance, consumer demand for lower-impact packaging, and expansion of applications in agriculture, healthcare, textiles, automotive components, and consumer products.

Table 2. Global bio-based plastics production and market indicators

Indicator	Reported Value
Global bio-based plastics production capacity, 2025	2.31 million tonnes
Actual global production, 2025	1.67 million tonnes
Average capacity utilization, 2025	72%
Projected global capacity, 2030	4.69 million tonnes
Approximate capacity growth, 2025–2030	103%
Approximate compound annual growth rate	15.2%
Share of global plastics production	Approximately 0.5%
Packaging share of bio-based plastics capacity, 2025	41.3%
Packaging capacity, 2025	Approximately 0.95 million tonnes
Automotive and transport share, 2025	10.3%
Automotive and transport capacity, 2025	Approximately 0.24 million tonnes

According to the 2025 market assessment of European Bioplastics and the nova-Institute, global bio-based plastics production capacity was approximately 2.31 million tonnes in 2025 and is projected to reach about 4.69 million tonnes by 2030 (De Jong *et al.* 2025). This corresponds to an approximate compound annual growth rate of 15.2% over the five-year period. Despite this projected doubling, bio-based plastics account for only about 0.5% of the approximately 431 million tonnes

of plastics produced globally each year, indicating a substantial difference between current production and the potential addressable market (De Jong *et al.* 2025).

Packaging remained the largest application segment in 2025, accounting for 41.3% or approximately 0.95 million tonnes of global bio-based plastics production capacity (De Jong *et al.* 2025). This dominance is relevant to chitosan-based materials because food packaging requires film formation, antimicrobial performance, oxygen and moisture control, mechanical integrity, optical protection, and compatibility with active agents. Chitosan–GO nanocomposites can potentially address several of these requirements simultaneously, although migration and oral-safety assessment are essential before food-contact commercialization. Demand is also diversifying beyond packaging. Bio-based polymers are increasingly being developed for textiles and fibres, consumer goods, agriculture and horticulture, automotive and transport components, coatings, construction products, electronics, and medical devices (De Jong *et al.* 2025). In healthcare, value is driven less by tonnage than by the need for biocompatible and degradable high-performance systems. Chitosan-based hydrogels, films, nanofibres, scaffolds, and nanocarriers are therefore relevant to wound management, tissue regeneration, controlled release, antimicrobial coatings, and diagnostic systems. (Kress *et al.* 2026; Song *et al.* 2009; Barrowclough and Birkbeck, 2022)

The market opportunity should nevertheless be interpreted carefully. The expressions bio-based and biodegradable describe different attributes. A polymer may be bio-based but non-biodegradable, such as bio-derived polyethylene, while a polymer may be biodegradable but produced partly from fossil feedstocks. Furthermore, biodegradable materials should complement rather than replace waste prevention, reuse, and recycling. Their greatest environmental value is expected in applications in which contamination, small dimensions, biological contact, or product design make conventional mechanical recycling impractical.

2.1.4 Relevance to Chitosan–graphene Oxide Nanocomposites

The scientific and commercial trends described above provide a strong rationale for research on CS–GO nanocomposites. Chitosan offers a renewable and biodegradable matrix, whereas graphene oxide can compensate for mechanical, barrier, adsorption, and functional deficiencies. The combination enables lower filler loading than conventional microcomposites because the high aspect ratio of GO can produce substantial interfacial effects at low concentration. This is particularly important for packaging and biomedical applications, where excessive nanofiller loading may reduce flexibility, transparency, biocompatibility, and

degradability. Future CS-GO development should therefore focus on safe-by-design formulations with low but effective GO loading, green oxidation and functionalization routes, non-toxic cross-linking, standardized biodegradation testing, quantitative GO-migration analysis, and life-cycle assessment. Market growth alone does not guarantee environmental benefit; the complete material system—including chitosan extraction, graphene oxide synthesis, energy use, additives, product lifetime, recovery, degradation products, and final disposal—must be considered.

3. CONSTITUENT MATERIALS

3.1 Chitin and chitosan

Chitin is a linear β -(1 $\rightarrow$ 4)-linked polysaccharide rich in N-acetyl-D-glucosamine. Its allomorphic forms— α , β , and γ —differ in chain packing and hydrogen-bond organization. Commercial chitosan is produced when chitin is deacetylated sufficiently to create a polymer rich in D-glucosamine units. The degree of deacetylation (DD), molecular weight, acetyl-group distribution, crystallinity, and source strongly influence solubility, viscosity, charge density, degradation, and biological behavior. In acidic media, $-\text{NH}_2$ groups become $-\text{NH}_3^+$, making chitosan one of the few naturally derived cationic polysaccharides (Khandegar *et al.* 2021; Rinaudo *et al.* 2006).

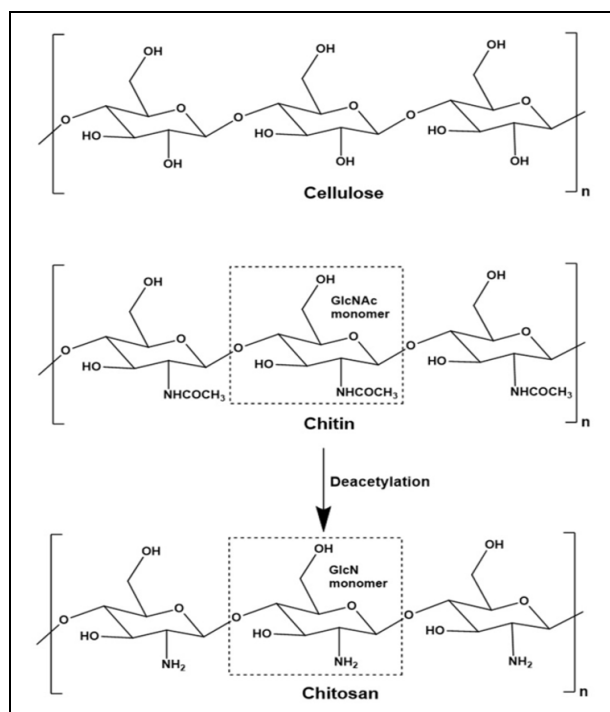


Fig. 2: Conversion of chitin to chitosan

Conventional extraction from shrimp or crab shells involves deproteinization with alkali, demineralization with acid, optional decolorization, and

concentrated-alkali deacetylation. A natural-waste-derived membrane study synthesized chitosan from shrimp shells and GO from coconut-shell-derived carbon, illustrating the potential to couple two waste streams into a higher-value composite (Saputra *et al.* 2022). Chemical extraction is fast and industrially established, but it consumes water and corrosive reagents and may degrade proteins that could otherwise be recovered. Fermentation and enzymatic alternatives reduce chemical burden but are slower and can be more difficult to control (Yang *et al.* 2010; Sabzevari *et al.* 2018; Promkatkaew *et al.* 2025)

3.2 Graphene Oxide

GO is generally prepared by oxidative exfoliation of graphite using variants of the Hummers method. Sulfuric acid and permanganate create oxygenated functionalities and increase interlayer spacing, permitting exfoliation into sheets. Oxidation level determines hydrophilicity, defect density, surface charge, conductivity, thermal stability, and interactions with chitosan. Excessive oxidation can improve dispersion but reduce electrical conductivity and introduce structural defects; insufficient oxidation can promote aggregation. GO properties are also sensitive to lateral size, thickness, purification, residual metals, and storage conditions.

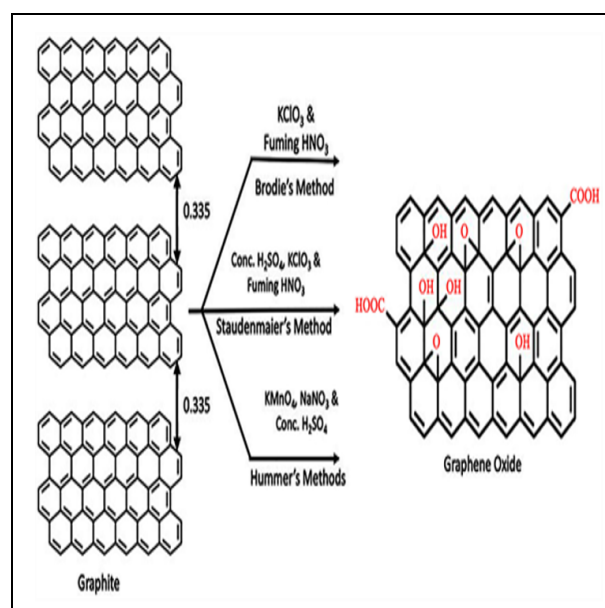


Fig. 3: Schematic representation of graphite oxidation to graphene oxide through the brodie, staudenmaier, and hummers methods, adapted from adetayo and runsewe (Adetayo *et al.* 2019)

3.2.1 GO Synthesis Routes, Sustainability and Green Alternatives

Conventional GO synthesis is dominated by Brodie, Staudenmaier and Hummers-type oxidation

routes. Brodie and Staudenmaier approaches use strong oxidants and acidic media and can be slow, hazardous and difficult to scale safely. The modified Hummers method is faster and widely used, but it still requires concentrated acid, permanganate, repeated washing and careful management of acidic effluents and residual metal ions. From a sustainability perspective, the GO route is therefore a major determinant of the environmental footprint of CS–GO materials. Greener

directions include electrochemical exfoliation, reduced-acid oxidation, microwave- or ultrasound-assisted oxidation, plant-extract-assisted reduction to rGO, recovery of process acids and oxidants, and the use of biomass-derived graphitic carbon. However, greener synthesis should be evaluated by measurable outputs such as oxidation level, C/O ratio, sheet size, defect density, wastewater volume, energy demand, yield and reproducibility rather than by the label “green” alone.

Table 3. Comparison of graphene-oxide synthesis routes, sustainability concerns, and scale-up implications

GO Route	Main Advantage	Sustainability Concern	Scale-up Implication
Modified Hummers	Fast, reproducible and widely reported	Strong acids, oxidants and washing effluent	Industrially possible only with closed-loop reagent and wastewater management
Electrochemical exfoliation	Lower chemical burden and tunable oxidation	Requires electrode control and electrical energy	Promising for cleaner GO if sheet quality is reproducible
Biomass-derived carbon oxidation	Uses renewable or waste carbon sources	Carbon purity and batch variability may affect GO quality	Attractive for circular materials but needs standardization
Ultrasound/microwave- assisted routes	Shorter reaction time and better dispersion	Energy input and local overheating must be controlled	Useful for laboratory-to-pilot optimization

Table 4. Complementary contributions of chitosan and graphene oxide in CS–GO nanocomposites

Feature	Chitosan Contribution	Graphene Oxide Contribution	Composite Benefit	Ref.
Surface chemistry	Primary amine and hydroxyl groups; pH-responsive protonation	Carboxyl, hydroxyl, epoxy, carbonyl groups; residual aromatic domains	Multiple noncovalent and covalent interactions; tunable adsorption and loading	(Khandegar <i>et al.</i> 2021; Saputra <i>et al.</i> 2022)
Processability	Film-, gel-, bead-, and fiber-forming biopolymer	Aqueous-dispersible high-aspect-ratio nanosheets	Shapeable membranes, hydrogels, scaffolds, nanofibers, particles and aerogels	(Naser <i>et al.</i> 2025; Ali <i>et al.</i> 2023)
Mechanical behavior	Flexible but mechanically modest	High intrinsic stiffness and aspect ratio	Improved tensile strength and modulus when dispersion is homogeneous	(Feng and Wang, 2022; El-Sheikh <i>et al.</i> 2025)
Biological function	Biodegradable, mucoadhesive, hemostatic, antimicrobial	Photothermal, adsorptive, antibacterial; dose-dependent toxicity concerns	Improved multifunctionality and potentially reduced GO cytotoxicity	(Promkatkaew <i>et al.</i> 2025; Su <i>et al.</i> 2021)
Environmental function	Metal chelation and anionic pollutant binding after protonation	Large surface area and affinity for aromatic/cationic contaminants	Broad-spectrum adsorption and improved recoverability	(Khandegar <i>et al.</i> 2021; Vo <i>et al.</i> 2024)
Electrical/optical function	Ionically conductive under humid conditions	Electronic/photothermal and optical response	Flexible sensing, dielectric and photothermal platforms	(Prokhorov and Luna-Bárcenas, 2020; Ahmed <i>et al.</i> 2023)

4. INTERFACIAL CHEMISTRY AND FORMATION MECHANISMS

4.1 Hydrogen Bonding and Electrostatic Self-assembly

The simplest route to CS–GO nanocomposites is aqueous self-assembly. GO is dispersed by sonication, whereas chitosan is dissolved in dilute acetic acid. At acidic pH, chitosan amino groups are protonated and

electrostatically attracted to deprotonated or partially ionized carboxyl groups on GO. Simultaneously, –OH and –NH groups of chitosan form hydrogen bonds with –OH, epoxide, and carboxyl groups of GO. These interactions can produce molecular-scale dispersion and efficient stress transfer. The foundational well-dispersed film study reported that only 1 wt% GO increased tensile strength and Young's modulus by approximately 122% and 64%, respectively, while also increasing elongation at break (Yang *et al.* 2010).

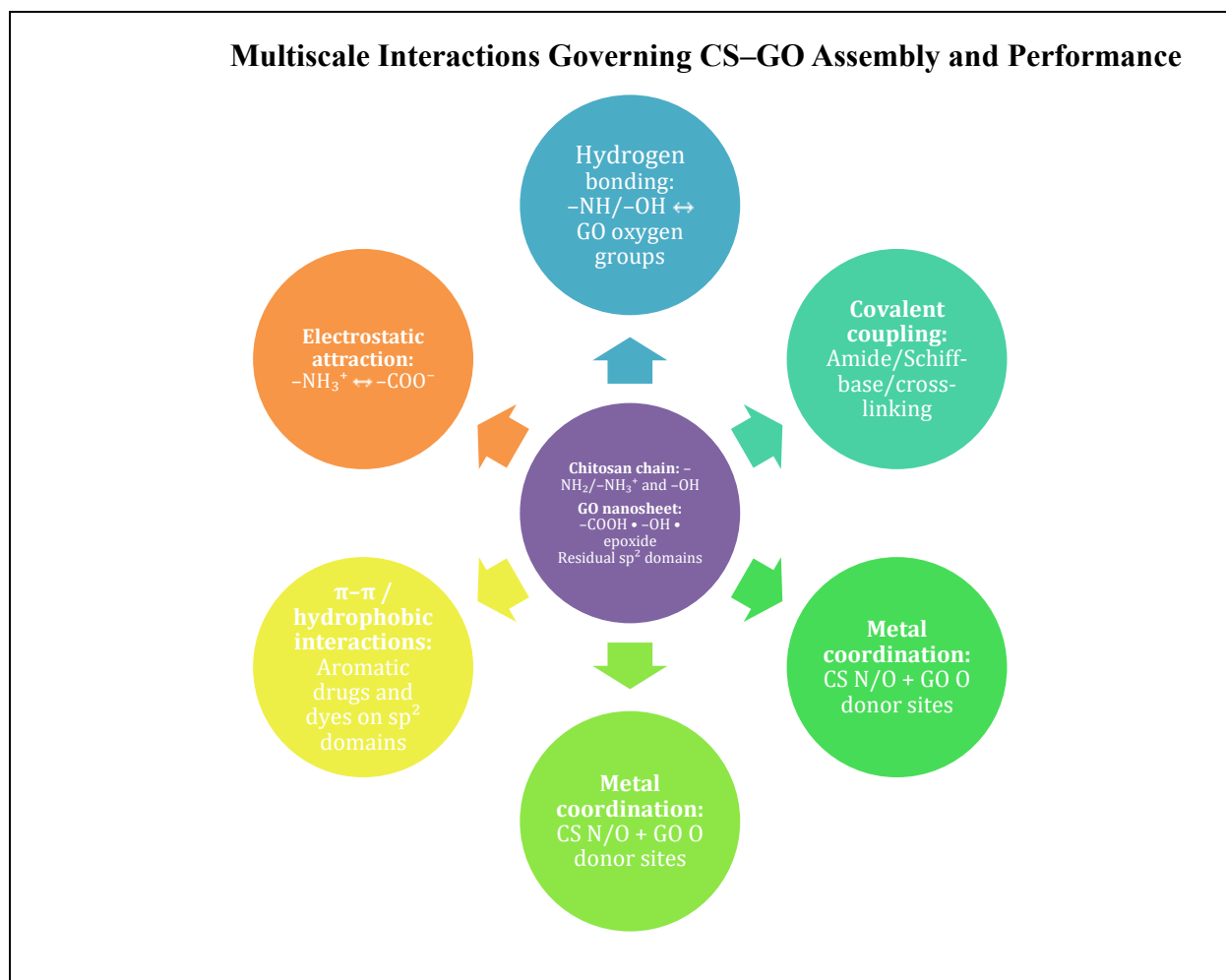


Fig. 4: Multiscale interactions governing CS–GO assembly, including hydrogen bonding, electrostatic attraction, covalent coupling, π–π/hydrophobic interactions, metal coordination, and loading-dependent dispersion, original author synthesis based on Refs. (Feng and Wang, 2022; Cobos *et al.* 2017; Yang *et al.* 2010; El-Sheikh *et al.* 2025; Emadi *et al.* 2017)

At low pH, protonated chitosan binds negatively charged GO through electrostatic attraction. The –OH and –NH₂ groups of chitosan form hydrogen bonds with GO hydroxyl, epoxy and carboxyl groups. Covalent composites are produced by carbodiimide-mediated amidation between GO carboxyl groups and chitosan amino groups, by aldehyde cross-linking, or by multifunctional cross-linkers. Strong interfacial adhesion transfers stress from the polymer to the rigid nanosheet and suppresses crack propagation. In adsorption systems, however, excessive cross-linking may consume amino

groups and reduce metal-binding capacity. The desired interface therefore depends on application: stable covalent networks for implants and reusable sorbents; reversible noncovalent assembly for responsive delivery and self-healing hydrogels. (Yang *et al.* 2010; El-Sheikh *et al.* 2025)

4.2 Covalent Coupling and Cross-linking

Covalent stabilization is used when resistance to swelling or desorption is required. Carboxyl groups on

GO can be activated by carbodiimide chemistry and coupled with chitosan amino groups to form amide bonds. Cross-linking can also involve glutaraldehyde, genipin, epichlorohydrin, or other multifunctional agents, although residual toxicity and loss of free adsorption sites must be considered. In a dye-treatment study, cross-linking GO with low-molecular-weight chitosan produced a stable composite with greater methylene-blue capacity than pristine GO. Spectroscopic evidence supported coupling between chitosan amines and GO carboxyl groups (Sabzevari *et al.* 2018).

4.3 π - π , Hydrophobic, and Coordination Interactions

Residual sp^2 domains in GO enable π - π interactions with aromatic dyes, drugs, and biomolecules. Hydrogen bonding and hydrophobic association contribute additional loading. Metal adsorption proceeds through coordination with amino and hydroxyl groups in chitosan and oxygen donors in GO (Massey *et al.* 2024). Computational studies indicate that chitosan nitrogen atoms can be dominant metal-binding sites, while GO modulates electronic structure and provides additional oxygen-containing coordination environments. In ternary composites, metal oxides or metallic nanoparticles introduce further coordination, catalytic, magnetic, antibacterial, or photothermal functions.

4.3.1 Molecular Simulation and Computational Modelling

Molecular simulations can strengthen interpretation of CS-GO interfaces by estimating

interaction energies, preferred binding sites and solvent effects that are difficult to isolate experimentally. Density functional theory (DFT) is useful for local bonding, charge transfer, adsorption energy and frontier-orbital analysis, while molecular dynamics (MD) can examine polymer-chain conformation, water structuring, ion diffusion and competitive adsorption at larger length scales. Hydrogen bonding between chitosan $-OH/-NH_2$ groups and GO oxygenated groups is often cooperative rather than a single isolated interaction; therefore, calculated hydrogen-bond energies should be interpreted together with hydration, pH-dependent protonation, chain mobility and counter-ion effects. QTAIM, NBO charge analysis, radial distribution functions and binding free-energy calculations can help distinguish electrostatic attraction, hydrogen bonding, metal coordination and π - π interactions. Computational claims should be validated against FTIR/XPS shifts, adsorption isotherms, zeta-potential changes and post-adsorption spectra.

4.4 Dispersion and Percolation

Performance depends critically on dispersion. At low loading, exfoliated GO acts as an efficient nanofiller and creates a tortuous diffusion path. At higher loading, sheet restacking and aggregation generate stress concentrators, reduce accessible area, and can increase cytotoxicity. Electrical properties may improve only after conductive pathways form, particularly when GO is partially reduced. Thus, an optimum filler range is application-specific and should be selected through combined mechanical, barrier, electrical, and biological testing rather than by maximizing GO concentration

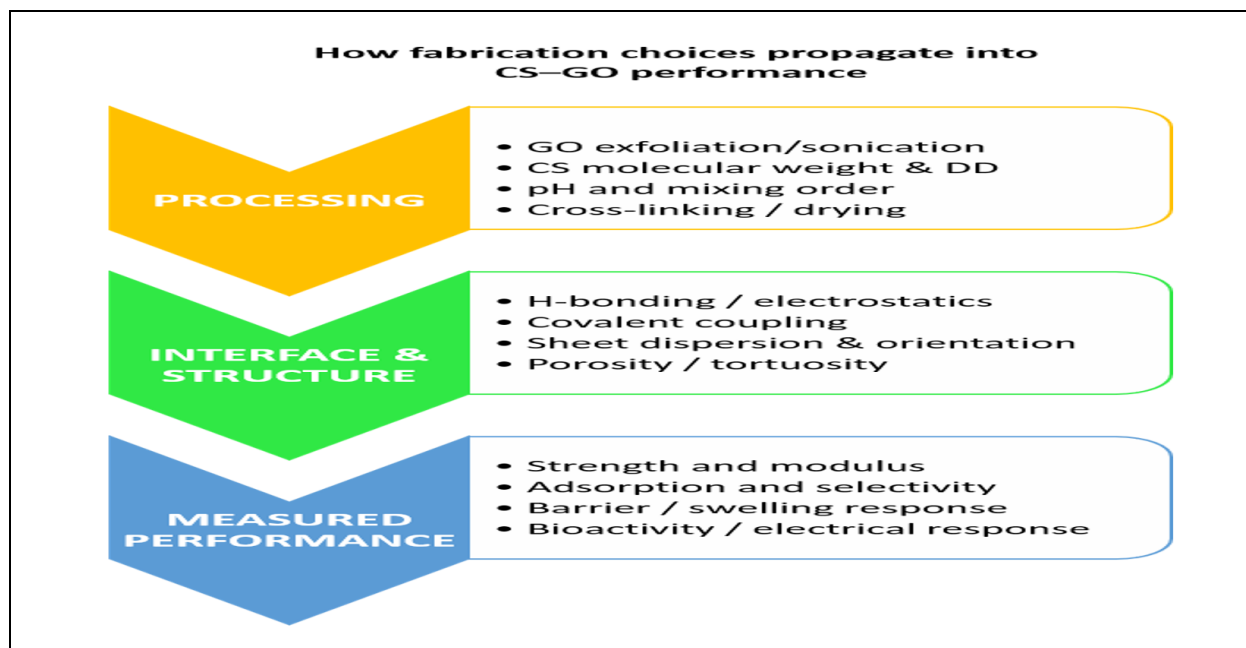


Fig. 5: Processing–structure–performance map for CS-GO nanocomposites, original author synthesis based on Refs. (Cobos *et al.* 2017; Yang *et al.* 2010; Prokhorov and Luna-Bárcenas, 2020; Ahmed *et al.* 2017)

5. FABRICATION STRATEGIES

Table 5. Comparison of principal CS–GO fabrication strategies and application-oriented trade-offs

Method	Typical Process	Advantages	Limitations / Critical Variables	Representative Use	References
Solution casting	Mix aqueous GO dispersion with acidic CS solution; cast and dry	Simple, low cost, scalable for films	Drying stress, residual acid, sheet orientation and aggregation	Packaging, membranes, wound films, dielectric films	(Khandegar <i>et al.</i> 2021; Feng and Wang, 2022)
Covalent conjugation	Activate GO carboxyl groups and react with CS amines	Stable interface; reduced GO release	Reagents may be toxic; free amines can be consumed	Drug carriers, stable membranes, biomedical films	(Saputra <i>et al.</i> 2022; El-Sheikh <i>et al.</i> 2025)
Electrospinning	Blend CS with carrier polymers and GO; apply high voltage	High surface area and porosity	CS spinnability, solvent selection and GO aggregation	Wound dressings, tissue scaffolds, sensors	(Naser <i>et al.</i> 2025; Ali <i>et al.</i> 2023)
Hydrogel formation	Physical or chemical cross-linking of CS–GO aqueous networks	Injectability, high water content, stimulus response	Poor mechanical stability unless reinforced	Drug delivery, wound healing, tissue engineering	(Promkatkaew <i>et al.</i> 2025; Su <i>et al.</i> 2021)
Freeze-drying / aerogels	Freeze composite dispersion and sublime ice	Porous 3D architecture and high uptake	Energy intensive; fragile structures	Adsorbents, scaffolds, hemostatic materials	(Moradi <i>et al.</i> 2021; Vo <i>et al.</i> 2024)
Beads / microspheres	Drop CS–GO dispersion into alkaline or cross-linking bath	Easy recovery and packed-bed handling	Mass-transfer limitations and swelling	Water treatment and controlled release	(Figueroa <i>et al.</i> 2020; Valencia-Llano <i>et al.</i> 2021)
Magnetic decoration	Incorporate Fe ₃ O ₄ or ferrite nanoparticles	Rapid magnetic separation and reuse	Possible pore blockage, leaching and reduced active sites	Heavy-metal and dye adsorption	(Sabzevari <i>et al.</i> 2018; Ahmed <i>et al.</i> 2023)
Metal/oxide decoration	Add Ag, ZnO, TiO ₂ or other nanoparticles	Antimicrobial, catalytic, optical or osteogenic function	Nanoparticle migration and toxicity concerns	Antibacterial coatings, photothermal systems, bone scaffolds	(Yang <i>et al.</i> 2010; Valencia-Llano <i>et al.</i> 2021)

5.1 Scalability, Industrial Feasibility and Reproducibility of Fabrication Routes

Laboratory fabrication routes should be assessed not only for material performance but also for reproducibility, solvent use, energy demand, batch-to-batch variation and compatibility with continuous processing. Solution casting is simple and inexpensive but can suffer from drying stresses and thickness variability. Electrospinning produces high-surface-area mats, but throughput and solvent recovery become

important at scale. Freeze-dried aerogels and scaffolds offer high porosity but require energy-intensive drying and careful mechanical handling. Beads, membranes and magnetic particles are more realistic for wastewater applications because they can be packed, recovered or regenerated. For biomedical and packaging applications, residual cross-linkers, sterilization, migration and regulatory documentation can dominate production cost. Therefore, future reports should include material yield, batch reproducibility, processing time, solvent/reagent consumption, and at least a preliminary cost or scale-up discussion.

Table 6. Scalability, reproducibility, and realistic translation pathways for common fabrication routes

Fabrication Route	Scalability	Cost/Reproducibility Issue	Most Realistic Translation Path
Solution casting	Moderate to high	Film thickness and drying history must be controlled	Packaging films, coatings and wound films
Electrospinning	Moderate	Low throughput unless multi-needle or needleless systems are used	Wound dressings and sensor mats
Freeze-drying/aerogels	Low to moderate	Energy intensive; fragile structures	High-value adsorbents and tissue scaffolds
Beads/microspheres	High	Mass-transfer limitations and swelling must be managed	Packed-bed water treatment and controlled release
Magnetic composites	Moderate	Nanoparticle leaching and cost of magnetic phase	Recoverable adsorbents and reusable catalysts

6. CHARACTERIZATION OF CS-GO NANOCOMPOSITES

A rigorous characterization strategy should establish whether graphene oxide has been successfully incorporated into the chitosan matrix, identify the physicochemical interactions formed between the two components, evaluate the uniformity of graphene oxide dispersion, and explain how the resulting structural and interfacial features influence the observed material performance. Because no single analytical technique can address all of these aspects conclusively, reliable interpretation requires complementary evidence from multiple characterization methods. (Emadi *et al.* 2017)

6.1 Fourier-transform infrared spectroscopy

FTIR is used to identify functional-group changes and interfacial interactions. Chitosan typically displays a broad O–H/N–H stretching envelope near 3200–3500 cm^{-1} , C–H stretching around 2870–2930 cm^{-1} , amide-I near 1640–1655 cm^{-1} , N–H bending near 1550–1600 cm^{-1} , and glycosidic C–O–C/C–O vibrations around 1020–1155 cm^{-1} . GO commonly exhibits broad O–H stretching, C=O near 1700–1735 cm^{-1} , aromatic C=C near 1580–1625 cm^{-1} , epoxy C–O–C near 1220–1260 cm^{-1} and alkoxy C–O near 1040–1080 cm^{-1} . In composites, band broadening, shifts and intensity reductions support hydrogen bonding and electrostatic complexation. Appearance of amide bands with simultaneous reduction of GO carboxyl intensity is stronger evidence of covalent amidation. One natural-waste-derived membrane study reported disappearance of chitosan's 891 cm^{-1} glucopyranose-related band and GO's 1704 cm^{-1} C=O feature, together with reduced C=C intensity at 1557 cm^{-1} , consistent with close physical interaction. (Vo *et al.* 2024; Ahmed *et al.* 2023; Figueroa

et al. 2020; Su *et al.* 2021; Valencia-Llano *et al.* 2021; Naser *et al.* 2025; Ali *et al.* 2023; Dinesu *et al.* 2019)

6.2 X-ray Diffraction

XRD evaluates GO interlayer spacing, chitosan semicrystallinity and phase changes caused by hybridization. GO prepared by oxidation often shows a low-angle (001) peak near $2\theta \approx 9\text{--}12^\circ$, while chitosan exhibits a broad semicrystalline reflection near $19\text{--}21^\circ$. Suppression or broadening of these peaks in the composite indicates disrupted chitosan packing and exfoliated or intercalated GO. In a waste-derived GO/CS membrane, peaks were reported at 19.3° for chitosan and 26.3° for the GO-containing material; the authors attributed reduced chitosan crystallinity to GO dominance. In magnetic $\text{CuFe}_2\text{O}_4/\text{CS}/\text{GO}$, the GO peak at 9.56° ($d \approx 9.3 \text{ \AA}$), chitosan feature at 20.1° and ferrite reflections were retained with reduced polymer/GO intensity, confirming phase integration without destroying the ferrite crystal structure.

6.3 Raman Spectroscopy and X-ray Photoelectron Spectroscopy

Raman spectroscopy tracks disorder and graphitic domains through the D band near 1340–1360 cm^{-1} and G band near 1570–1600 cm^{-1} . The ID/IG ratio increases when oxidation or functionalization introduces defects and can change after reduction, cross-linking or strong polymer interaction. XPS directly quantifies C–C/C=C, C–O, C=O and O–C=O components and detects nitrogen from chitosan. A new amide N–C=O component or shifts in N 1s/C 1s binding energies provide direct support for covalent coupling. Reporting only survey spectra is insufficient; peak deconvolution, atomic ratios and fitting constraints should be included.

Table 7. Characterization methods, key observations, comparison with previous studies for CS–GO composites

Technique	Typical CS–GO Observation	Comparison with Previous Studies	Interpretation	Ref
FTIR	Broadening/shifting of O–H/N–H; changes in C=O and amide bands	(Saputra <i>et al.</i> 2022) reported disappearance of 891 and 1704 cm ⁻¹ features and reduced C=C intensity	Hydrogen bonding, electrostatic interaction, or covalent coupling depending on spectral changes	(Saputra <i>et al.</i> 2022; Figueroa <i>et al.</i> 2020; Ali <i>et al.</i> 2023; Emadi <i>et al.</i> 2017)
XRD	Reduction/broadening of CS and GO peaks	CS commonly shows 19–21°; GO 9–12°; magnetic CS–GO systems retain ferrite crystalline peaks	Exfoliation, intercalation, reduced crystallinity, or coexistence of inorganic phases	(Khandegar <i>et al.</i> 2021; Saputra <i>et al.</i> 2022; El-Sheikh <i>et al.</i> 2025; Emadi <i>et al.</i> 2017)
Raman	D and G bands with altered I _D /I _G	Previous CS–GO studies use I _D /I _G variation to monitor functionalization/reduction	Defect density and graphitic-domain evolution	(Promkatkaew <i>et al.</i> 2025; Su <i>et al.</i> 2021; Emadi <i>et al.</i> 2017)
XPS	C 1s, O 1s, N 1s changes; amide environments	Earlier covalent systems report N–C=O and binding-energy shifts	Strong evidence of surface chemical modification	(Moradi <i>et al.</i> 2021; Saputra <i>et al.</i> 2022; Vo <i>et al.</i> 2024; Emadi <i>et al.</i> 2017)
SEM/TEM/AFM	Distributed sheets, rough fracture surfaces, porous networks	Well-dispersed GO correlates with improved mechanical performance	Dispersion, aggregation, pore morphology	(Sabzevari <i>et al.</i> 2018; Prokhorov and Luna-Bárcenas, 2020; Ahmed <i>et al.</i> 2023; Emadi <i>et al.</i> 2017)
TGA/DSC	Modified decomposition temperature and chain mobility	GO may improve thermal stability, but highly oxidized GO can accelerate degradation	Polymer confinement and oxidation-dependent thermal behavior	(Yang <i>et al.</i> 2010; Promkatkaew <i>et al.</i> 2025; Emadi <i>et al.</i> 2017)
Mechanical testing	Increased tensile strength/modulus at optimum GO loading	1 wt% GO: tensile strength +122%, modulus +64% in a well-dispersed system [9]	Efficient stress transfer at strong CS–GO interfaces	(Sabzevari <i>et al.</i> 2018; Valencia-Llano <i>et al.</i> 2021; Emadi <i>et al.</i> 2017)
BET/porosimetry	Surface area may decrease after CS coating	High adsorption can still occur despite lower BET area	Functional-group chemistry can dominate over total surface area	(Prokhorov and Luna-Bárcenas, 2020; Ahmed <i>et al.</i> 2023; Emadi <i>et al.</i> 2017)
Zeta potential	pH-dependent surface-charge change	Earlier adsorption studies link protonated CS with negatively charged GO	Electrostatic assembly and adsorption mechanism	(Khandegar <i>et al.</i> 2021; El-Sheikh <i>et al.</i> 2025; Emadi <i>et al.</i> 2017)
Biological assays	Viability, hemolysis, antimicrobial and inflammatory response	Application-specific safety and efficacy	Dose, sheet size and exposure route must be specified	(Moradi <i>et al.</i> 2021; Saputra <i>et al.</i> 2022; Emadi <i>et al.</i> 2017)

6.4 Electron Microscopy, AFM, Particle Size, and Dispersion

SEM reveals surface texture, fracture morphology and pore architecture, whereas TEM can establish whether GO sheets remain individually

dispersed or form stacked tactoids. Molecular-scale dispersion produces rough, tortuous fracture surfaces and sheet pull-out rather than large agglomerates. AFM provides sheet thickness and roughness; DLS is appropriate for nanoparticle dispersions but not for bulk films. Smooth GO/CS surfaces have been attributed to

contact between chitosan hydroxyl/amino groups and oxygenated GO. For porous scaffolds, pore size distribution, interconnectivity and wall thickness must be quantified because cell infiltration and mass transfer depend on these parameters.

6.5 Thermal, Mechanical, Barrier, Porosity, and Surface Analysis

TGA and DSC distinguish water loss, polymer decomposition and GO-mediated thermal stabilization. GO may increase char yield and delay chain degradation through restricted segmental mobility, although strongly oxidized GO can catalyze early decomposition. Tensile testing should report specimen geometry, conditioning humidity, strain rate, replicate number and complete stress-strain curves. Barrier testing should specify film thickness and relative humidity. BET surface area can decrease after chitosan coating because polymer blocks GO pores, yet adsorption may still improve because new amino groups create high-affinity coordination sites; therefore, surface area alone does not predict adsorption performance.

6.6 Integrated Interpretation and Evidence Hierarchy

Reliable characterization requires an evidence hierarchy rather than isolated peak assignment. For noncovalent composites, the strongest interpretation combines FTIR band shifts, zeta-potential changes, XRD evidence of altered chain packing, and microscopy demonstrating exfoliated sheets without large tactoids. For covalently coupled materials, FTIR should be supported by high-resolution XPS deconvolution showing new amide environments, changes in elemental ratios, and stability in competitive solvents. Mechanical reinforcement should be correlated with fracture-surface morphology and complete stress-strain curves. Adsorption mechanisms require pre- and post-adsorption spectroscopy, pH-dependent uptake, ionic-strength tests, metal or dye speciation, kinetic analysis, and desorption behavior. Biomedical claims must be supported by characterization in the actual exposure medium, because proteins, salts, pH, and serum can alter aggregation, surface charge, and cellular uptake.

6.7 Advanced and *in situ* Characterization Requirements

Beyond conventional FTIR, XRD and microscopy, future CS-GO studies should use spatially resolved and *in situ* techniques where possible. Raman mapping can reveal whether GO is homogeneously distributed or locally aggregated across films, fibers and membranes. Quantitative XPS should report C/O and

N/C ratios, amide components, protonated amine fractions and fitting constraints rather than only survey spectra. SAXS can provide information on nanosheet spacing, hierarchical porosity and polymer-chain organization in hydrated states. Rheological measurements are important for hydrogels, inks and printable formulations because storage modulus, loss modulus, yield stress and shear-thinning behavior govern injectability, coating uniformity and printability. *In situ* FTIR, electrochemical impedance spectroscopy, operando Raman, quartz-crystal microbalance and time-resolved swelling studies can track adsorption, reduction, hydration and ion-transport events under working conditions instead of only before-and-after states.

7. STRUCTURE-PROPERTY RELATIONSHIPS

7.1 Mechanical Reinforcement

GO reinforces chitosan through its high aspect ratio, stiffness, and strong interfacial interactions. Efficient reinforcement requires exfoliation and load transfer. The well-dispersed composite reported a 122% increase in tensile strength and 64% increase in Young's modulus with only 1 wt% GO (Yang *et al.* 2010). Another membrane review summarized a covalently cross-linked system in which tensile strength rose from 43.2 to 104.2 MPa at 1 wt% GO. These gains are not universal: aggregation, inadequate interfacial adhesion, or excessive filler can lower elongation and create brittle films.

7.1.1 Influence of GO Loading, Chitosan Molecular Weight and Degree of Deacetylation

The reinforcing effect of GO is strongly non-linear. Very low loadings can improve strength and modulus when sheets are exfoliated and aligned, but excessive loading promotes restacking, opacity, brittle fracture and reduced accessible surface area. The optimum GO concentration is therefore application-specific: packaging and biomedical films usually require low loading to preserve flexibility, transparency and safety, whereas adsorption systems may tolerate higher loading if functional groups remain accessible. Chitosan molecular weight affects chain entanglement, viscosity, film strength and solution processability. High-molecular-weight chitosan generally improves mechanical integrity but may hinder homogeneous GO dispersion; low-molecular-weight chitosan improves coating of GO and mass transfer but may reduce film toughness. Degree of deacetylation controls amine density, protonation, metal coordination, antimicrobial action and cross-linking capacity. Consequently, DD and molecular weight should be reported with GO loading in every study, and performance should be normalized to actual rather than nominal GO content.

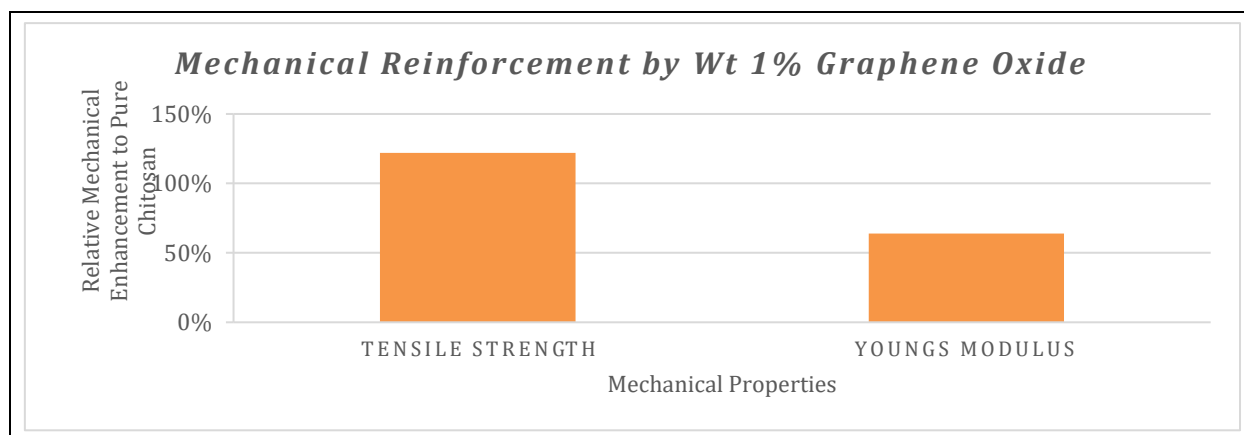


Fig. 6: Relative mechanical enhancement reported for a molecularly dispersed chitosan film containing 1 wt% graphene oxide

7.2 Barrier and Swelling Behavior

GO sheets can create tortuous pathways that slow diffusion of water vapor, gases, and solutes. Cross-linking reduces chitosan dissolution and swelling, improving dimensional stability in water. Conversely, abundant oxygen functionalities increase hydrophilicity and may raise water uptake. The net barrier response therefore reflects sheet orientation, cross-link density, plasticizer content, free volume, and environmental humidity.

7.3 Adsorption Capacity and Selectivity

Adsorption depends on electrostatic attraction, chelation, ion exchange, hydrogen bonding, π - π stacking, and pore diffusion. Chitosan is especially effective for metal complexation through $-\text{NH}_2$ and $-\text{OH}$ groups, whereas GO interacts strongly with aromatic and cationic organic pollutants. pH governs protonation and metal speciation and is often the dominant experimental variable. Composite selectivity can be rationalized using hard-soft acid-base interactions, functional-group accessibility, and hydrated-ion size. Cross-linking improves reusability but may consume amino groups; magnetic decoration facilitates separation but can dilute active polymer and block pores. (Mehdizadeh *et al.* 2020; Fazial and Tan, 2021)

7.4 Electrical, Optical, and Photothermal Properties

GO and partially reduced GO introduce dielectric, electronic, and optical responses absent from pristine chitosan. A study of CS-GO films containing 0–15 wt% GO reported anomalous negative electrical tunability: dielectric constant increased and resistivity decreased with DC bias, attributed to reversible GO-to-rGO transformation mediated by protons from water, GO groups, and protonated chitosan. This behavior suggests flexible gate dielectrics and humidity-sensitive devices

(Prokhorov and Luna-Bárcenas, 2020) GO also absorbs near-infrared light and converts it to heat, enabling photothermal antibacterial or anticancer systems.

8. ENVIRONMENTAL APPLICATIONS

8.1 Heavy-metal Removal

Heavy-metal remediation is one of the most established uses of CS-GO composites. Chitosan provides amino and hydroxyl coordination sites, while GO supplies oxygen donors, high interfacial area, and structural reinforcement. Adsorption generally increases with pH until precipitation or competing hydrolysis becomes important. Kinetic data frequently follow pseudo-second-order models, consistent with strong chemical interactions, although this model alone does not prove chemisorption.

A 2025 combined computational and experimental study examined CS/graphene and CS/GO binding with hydrated Pb and Cu. Composite formation lowered the calculated HOMO-LUMO gap and changed total dipole moment, indicating increased reactivity. Calculated adsorption energies were -13.869 eV for CS/graphene/Pb, -13.689 eV for CS/graphene/Cu, -12.975 eV for CS/GO/Pb, and -14.211 eV for CS/GO/Cu. QTAIM and FTIR supported the proposed interactions (El-Sheikh *et al.* 2025). Although such calculations illuminate binding trends, absolute energies depend strongly on the molecular model and solvent representation and should be correlated with batch adsorption and regeneration data.

Magnetic recovery addresses a major weakness of nanoscale adsorbents. A $\text{Fe}_3\text{O}_4/\text{GO}/\text{CS}$ nanocomposite achieved a Langmuir maximum Pb(II) capacity of 63.45 mg g^{-1} and pseudo-second-order fitting with $R^2 = 0.999$. The adsorbent was magnetically recovered and showed only about a 12% reduction in removal efficiency after four adsorption-desorption cycles (Vo *et al.* 2024). This

combination of uptake, separation, and regeneration is more relevant to practical operation than high equilibrium capacity alone. (Najafabadi *et al.* 2020; Mahmoudi *et al.* 2017; Francolini *et al.* 2019; Grande *et al.* 2017; Tran *et al.* 2017)

Recent magnetic-ferrite systems provide a stronger test of adsorption rate and regeneration. A $\text{NiFe}_2\text{O}_4\text{-GO-CS}$ adsorbent reported 99.07% Cd(II) recovery and an adsorption quantity of 396.29 mg g^{-1} within 14 min. After five adsorption-desorption cycles,

the reported recovery remained 86.72% with 346.89 mg g^{-1} retained capacity (Bulin and Guo, 2025). The study linked uptake to carbonyl, C–O, amide, amine, and hydroxyl donor sites and interpreted the metal–ligand interaction using hard–soft acid–base concepts. Such results strengthen the case for magnetically recoverable CS–GO sorbents, but their value for industrial treatment will ultimately depend on leaching, ferrite stability, regeneration chemistry, and performance in competitive real waters.

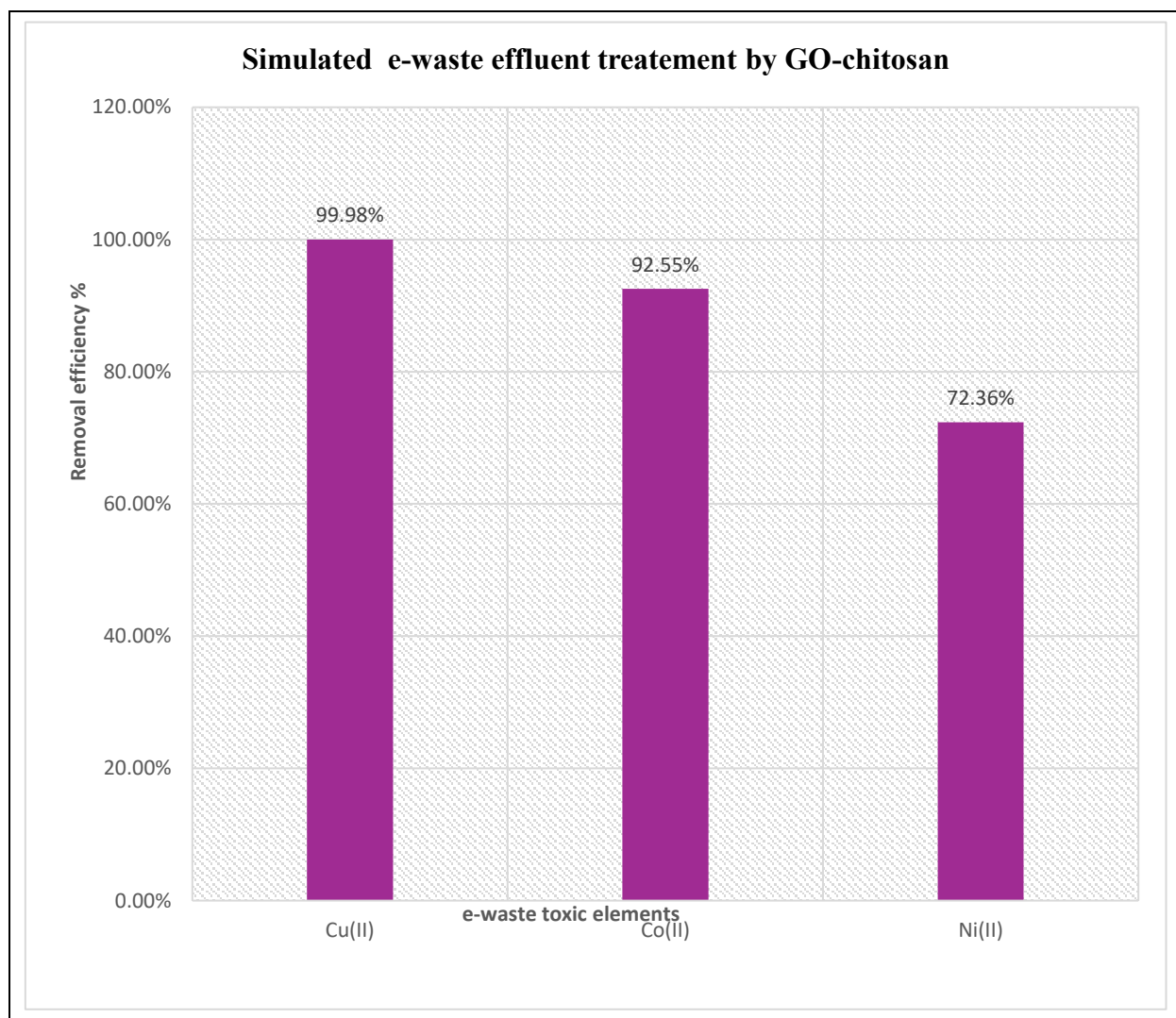


Fig. 7: Removal efficiencies reported for Cu(II), Co(II), and Ni(II) from simulated electronic-waste effluent using a GO–chitosan composite

8.2 Electronic-waste Effluents

Electronic waste contains valuable and toxic metals and is increasingly important as electronic-device consumption grows. A GO–CS composite tested with simulated e-waste effluent removed 99.98% Cu(II) at pH 7 in 30 min, 92.55% Co(II) at pH 9 in 120 min, and 72.36% Ni(II) at pH 5 in 180 min. Molecular-dynamics simulations identified chitosan nitrogen atoms as

principal coordination sites and indicated the strongest affinity for Cu(II) . The study also showed that low BET surface area did not preclude high performance, highlighting the importance of functional-group chemistry (Promkatkaew *et al.* 2025). Future work should use genuine leachates containing competing ions, organic additives, and extreme acidity, and should evaluate metal recovery rather than disposal of loaded sorbents.

8.3 Dye Removal and Model Organic Pollutants

CS-GO composites remove cationic and anionic dyes through different combinations of electrostatic attraction, π - π stacking, hydrogen bonding, and diffusion. A cross-linked GO-chitosan material reached a methylene blue monolayer capacity of 402.6 mg g^{-1} compared with 286.9 mg g^{-1} for GO, and showed faster pseudo-second-order uptake (Sabzevari *et al.* 2018). Magnetic $\text{CuFe}_2\text{O}_4/\text{CS}/\text{GO}$ prepared under ultrasound adsorbed indigo carmine and safranin O with capacities of 112.6 and 66.15 mg g^{-1} , respectively, and retained performance over five adsorption-desorption cycles (Ahmed *et al.* 2023). These systems illustrate how magnetic ferrites combine broad dye affinity with facile recovery.

High-capacity dye removal is also possible when chelating functionality and magnetic recovery are combined. An EDTA- and chitosan-functionalized magnetic GO nanobiocomposite achieved a maximum Rhodamine B adsorption capacity of approximately 1085.3 mg g^{-1} and remained reusable over seven cycles, with removal efficiency still above 80% and only a small loss in adsorption capacity (Marnani and Shahbazi,

2019). The authors attributed uptake to coupled physical and chemical interactions. This unusually high capacity should nevertheless be interpreted within its study-specific concentration, pH, and isotherm conditions rather than as a universal ranking against other CS-GO adsorbents.

8.4 Emerging Contaminants: PFAS and Artificial Sweeteners

Recent studies extend CS-GO adsorption beyond conventional metals and dyes toward persistent and emerging contaminants. Mahanty *et al.* developed a crosslinker-free chitosan-functionalized GO adsorbent using ultrasonication and systematically varied the CS:GO ratio from 2:1 to 10:1. The optimized GO-CS₈ formulation (8:1) showed a Langmuir maximum PFOA capacity of approximately 640 mg g^{-1} . Response-surface optimization predicted about 91% PFOA removal at 0.3 g L^{-1} adsorbent dose, pH 4, and 60-min contact time, and the material retained appreciable performance over four regeneration cycles in a complex water matrix (Mahanty *et al.* 2026).

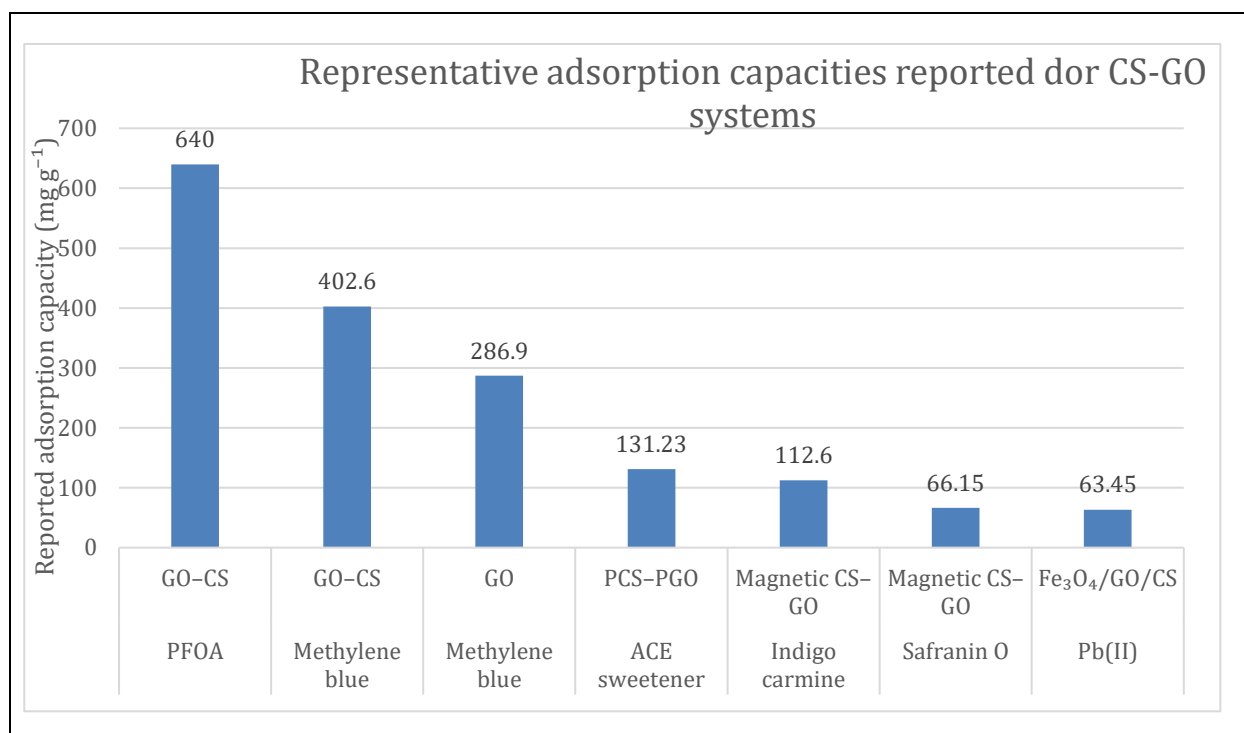


Fig. 8: Representative adsorption capacities reported for selected CS-GO systems, including recent PFOA and artificial-sweetener studies, experimental conditions differ substantially among studies; values should not be interpreted as a direct ranking (Sabzevari *et al.* 2018; Vo *et al.* 2024; Ahmed *et al.* 2023; Mahanty *et al.* 2026; Sun *et al.* 2026)

A 2026 bioinspired polyethyleneimine-modified chitosan-GO aerogel, designed to mimic the outwardly curled architecture of morning-glory petals, achieved an acesulfame-potassium adsorption capacity of 131.23 mg g^{-1} and a removal efficiency of 98.42%.

Multiscale characterization, density-functional-theory calculations, and molecular-dynamics simulations attributed adsorption mainly to electrostatic attraction and hydrogen bonding, while life-cycle assessment and biodegradation tests were used to examine sustainability

(Sun *et al.* 2026). These results illustrate the field's transition from single-solute proof-of-concept studies toward structure-guided adsorbents evaluated using mechanistic modelling, complex matrices, regeneration, and life-cycle criteria.

Microplastics have recently emerged as another relevant target. A 2026 NH₂-MIL-101(Fe)/CS/GO cross-linked nanocomposite removed 93.8% of polyethylene terephthalate (PET) and 89.7% of polystyrene (PS) microplastics at pH 6.2 with a 40 min contact time. Reported maximum adsorption capacities were 321.4 mg g⁻¹ for PET and 255.1 mg g⁻¹ for PS, while 92.5% removal efficiency was maintained after six cycles (Yakout *et al.* 2026). The result shows how MOF porosity, positively charged chitosan domains, GO surface area, and hydrophobic/ π interactions can be combined for emerging-contaminant capture, but nanoparticle/MOF stability and performance in mixed municipal wastewater remain important validation needs.

8.5 Membranes, Filtration, and Antifouling

Immobilizing GO in a chitosan-containing membrane reduces the risk of nanosheet release and enables pressure-driven filtration, adsorption, and antimicrobial action in a single material. GO can improve hydrophilicity and create selective channels, while chitosan binds metals and microorganisms. However, swelling, compaction, pH sensitivity, and long-term GO migration remain concerns. Membrane evaluation should report permeability–selectivity trade-offs, fouling resistance, cleaning recovery, mechanical integrity, and continuous-flow performance.

Beyond pollutant adsorption, CS–GO mixed-matrix membranes have also been evaluated for desalination. A pervaporation membrane containing 1 wt% GO reached a permeate flux of 30.0 kg m⁻² h⁻¹ while rejecting 99.99% salt from a 5 wt% NaCl feed at 81 °C (Qian *et al.* 2018). The study associated performance with good GO–chitosan compatibility, increased hydrophilicity, and distinct water/salt transport kinetics. This example broadens the environmental scope from batch adsorption to membrane-based high-salinity treatment, although thermal energy demand, long-term swelling, fouling, and module-scale stability must be considered in sustainability comparisons.

8.6 Environmental Limitations

Most studies use single-solute synthetic water at laboratory scale. Real effluents contain salts, natural organic matter, competing metals, surfactants, and suspended solids that may suppress adsorption. Regeneration often employs acid, base, or chelating agents and may create a concentrated secondary waste. Environmental claims should therefore include sorbent production burden, reagent recovery, regeneration chemistry, nanoparticle release, and end-of-life management. Life-cycle assessment and techno-economic analysis are necessary to determine whether waste-derived chitosan and carbon precursors provide a genuine advantage over activated carbon, ion-exchange resins, or conventional membranes (Travlou *et al.* 2013; Bao *et al.* 2011; Ma *et al.* 2020; Ahmed *et al.* 2017; Croitoru *et al.* 2020; Liu *et al.* 2018).

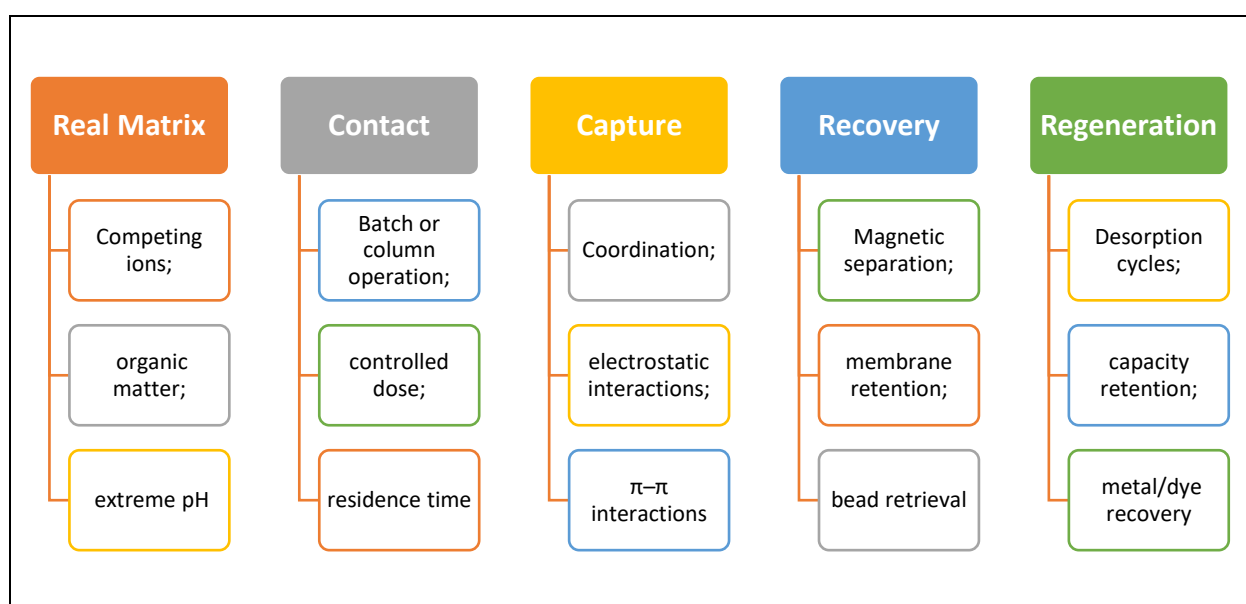


Fig. 9: Experimental workflow required to translate CS–GO remediation from model solutions to real treatment systems, original author synthesis based on Refs. (Promkatkaew *et al.* 2025; Vo *et al.* 2024; Ahmed *et al.* 2023; Tran *et al.* 2017; Croitoru *et al.* 2020)

Table 8. Quantitative comparison of representative environmental-remediation studies, including adsorption/removal performance, operating conditions, and reuse behavior

Composite	Target	Performance	Experimental Conditions/model	Reuse	Ref
GO–LCTS cross-linked film	Methylene blue	402.6 mg g ⁻¹	Pseudo-second-order; study-specific batch conditions; GO control: 286.9 mg g ⁻¹	Facile film recovery	(Promkatkaew <i>et al.</i> 2025; Vo <i>et al.</i> 2024)
GO/Fe ₃ O ₄ /CS	Pb (II)	63.45 mg g ⁻¹	Langmuir; pseudo-second-order (R ² = 0.999); exothermic; study-specific pH and dose	~12% decline after 4 cycles	(Promkatkaew <i>et al.</i> 2025; Vo <i>et al.</i> 2024)
GO–CS e-waste composite	Cu (II)	99.98% removal	pH 7; 30 min; N coordination	High selectivity/fast uptake	(Vo <i>et al.</i> 2024; El-Sheikh <i>et al.</i> 2025; Ahmed <i>et al.</i> 2023)
GO–CS e-waste composite	Co (II)	92.55% removal	pH 9; 120 min	Longer equilibration	(Vo <i>et al.</i> 2024; El-Sheikh <i>et al.</i> 2025; Ahmed <i>et al.</i> 2023)
GO–CS e-waste composite	Ni (II)	72.36% removal	pH 5; 180 min	Lower affinity	(Vo <i>et al.</i> 2024; El-Sheikh <i>et al.</i> 2025; Ahmed <i>et al.</i> 2023)
Magnetic CuFe ₂ O ₄ /CS/GO	Indigo carmine	112.6 mg g ⁻¹	Endothermic and spontaneous; study-specific pH and dose	Stable for 5 cycles	(Vo <i>et al.</i> 2024; El-Sheikh <i>et al.</i> 2025; Ahmed <i>et al.</i> 2023)
Magnetic CuFe ₂ O ₄ /CS/GO	Safranin O	66.15 mg g ⁻¹	Multiple isotherm models; study-specific pH and dose	Stable for 5 cycles	(Vo <i>et al.</i> 2024; El-Sheikh <i>et al.</i> 2025; Ahmed <i>et al.</i> 2023)
GO–CS_8 crosslinker-free adsorbent	PFOA	q _{max} ≈ 640 mg g ⁻¹ ; optimized removal ≈ 91%	Langmuir; pseudo-second-order; pH 4; 60 min; complex-matrix selectivity	Appreciable performance through 4 cycles	(Mahanty <i>et al.</i> 2026)
PCS–PGO bioinspired aerogel	Acesulfame-K	131.23 mg g ⁻¹ ; 98.42% removal	Multiscale spectroscopy + DFT/MD; complex artificial-sweetener mixtures	Biodegradation and life-cycle assessment reported	(Sun <i>et al.</i> 2026)
NiFe ₂ O ₄ –GO–CS	Cd(II)	396.29 mg g ⁻¹ ; 99.07% recovery	14 min equilibrium; multiple O/N donor sites; HSAB-supported mechanism	86.72% recovery after 5 cycles	(Bulin and Guo, 2025)
CS–EDTA–mGO	Rhodamine B	q _{max} ≈ 1085.3 mg g ⁻¹	Coupled physical/chemical adsorption; magnetic separation	>80% removal after 7 cycles	(Marnani and Shahbazi, 2019)
NH ₂ –MIL-101(Fe)/CS/GO	PET / PS microplastics	321.4 / 255.1 mg g ⁻¹ ; 93.8% / 89.7% removal	pH 6.2; 40 min; electrostatic, hydrophobic and π interactions	92.5% efficiency after 6 cycles	(Yakout <i>et al.</i> 2026)
CS/GO mixed-matrix membrane	5 wt% NaCl desalination	30.0 kg m ⁻² h ⁻¹ flux; 99.99% salt rejection	Pervaporation at 81 °C; 1 wt% GO	Long-term module stability not established	(Qian <i>et al.</i> 2018)

For industrial wastewater treatment, the most important unresolved issues are regeneration cost, long-term stability and performance in real matrices. Acid or chelator-based regeneration may restore adsorption sites but can create concentrated secondary waste and reduce material lifetime. Pilot-scale studies should therefore report breakthrough curves, bed volumes treated, pressure drop, regeneration chemicals, capacity loss per cycle, GO or nanoparticle leaching, sludge handling and contaminant recovery. Real textile, electroplating, mining, pharmaceutical and e-waste effluents contain competing ions, variable pH, surfactants and natural organic matter; these conditions should replace single-solute model waters before industrial claims are made.

9. BIOMEDICAL APPLICATIONS

9.1 Drug and Biomacromolecule Delivery

GO offers a large aromatic surface for drug adsorption through π - π stacking, while chitosan provides pH-responsive protonation, mucoadhesion, biocompatibility, and improved aqueous stability. CS-GO carriers have been fabricated as nanoparticles, hydrogels, films, and injectable networks. Acidic environments can protonate chitosan and weaken or reorganize interactions, enabling pH-responsive release. Targeting ligands, magnetic nanoparticles, and

thermosensitive polymers can add active targeting, imaging, or externally triggered release.

A covalently bonded GO-CS nanocomposite designed for proanthocyanidin delivery contained about 44 wt% chitosan, had an average hydrodynamic diameter of approximately 480 nm, loaded about 20 wt% grape-seed extract, and released 28.4 wt% extract per gram of nanocomposite under simulated physiological conditions. At 500 $\mu\text{g mL}^{-1}$ after 24 h, the GO-CS-extract formulation produced 97% HEK293 cell survival compared with 11% for raw extract and 48% for unloaded GO-CS, indicating that formulation altered both delivery and toxicity (Figuerola *et al.* 2020).

A multifunctional CS/AgNP/GO system demonstrated pH-dependent single and dual release of model compounds, antibacterial activity against *E. coli* and *S. aureus*, and near-infrared photothermal conversion. At pH 7.4, methylene-blue release from chitosan showed an initial burst followed by 70–80% release after 40–50 h, while fluorescein loaded on GO reached about 45% over 240 h; both released faster at pH 4 (Su *et al.* 2021). Such platforms are promising but require pharmacologically relevant drugs, validated loading states, serum stability, pharmacokinetics, and in vivo safety.

Table 9. Representative biomedical CS-GO systems, reported performance, and functional rationale

System	Application	Representative Result	Functional Rationale	Ref
GO-CS-proanthocyanidin nanoparticles	Phytodrug delivery	~20 wt% loading; 28.4 wt% release per g carrier; 97% cell survival	π - π and hydrophilic interactions; covalent CS-GO	(Figuerola <i>et al.</i> 2020; Su <i>et al.</i> 2021)
CS/AgNP/GO composite	Dual drug release and photothermal therapy	MB 70–80% at 40–50 h; fluorescein ~45% at 240 h	pH-sensitive CS plus GO adsorption and NIR response	(Figuerola <i>et al.</i> 2020; Su <i>et al.</i> 2021)
CS-GO films/hydrogels	Wound dressing	Improved barrier, antimicrobial action and exudate control	CS haemostasis + GO reinforcement	(Su <i>et al.</i> 2021; Valencia-Llano <i>et al.</i> 2021)
CS/GO/TiO ₂ /plant-extract beads	Bone regeneration	New bone evidenced after 90 days in defect model	Porous support and osteoinductive cues	(Su <i>et al.</i> 2021; Valencia-Llano <i>et al.</i> 2021)
GO-CS enzyme nanofibers	Biosensing	Low detection limits and high sensitivity reported across platforms	Enzyme immobilization and electron transfer	(Figuerola <i>et al.</i> 2020; Ahmed <i>et al.</i> 2023)

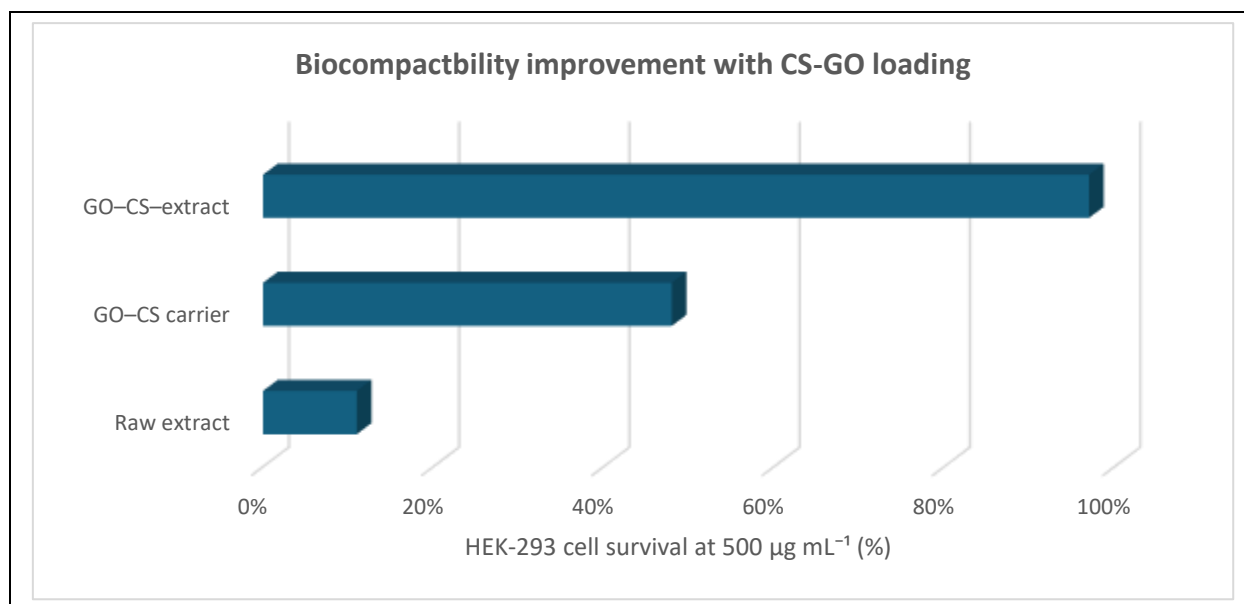


Fig. 10: HEK-293 cell-survival comparison illustrating improved compatibility after loading proanthocyanidins into a GO-CS carrier

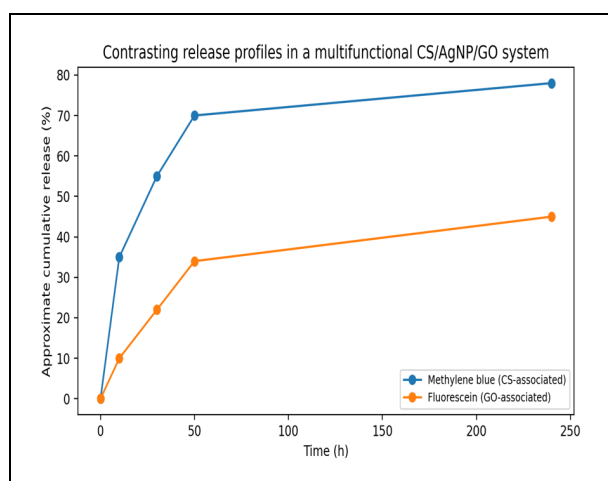


Fig. 11: Reconstructed release profiles showing faster chitosan-associated methylene blue release and slower GO-associated fluorescein release

9.1.1 Nanoparticle Carriers, Targeting, and Charge-Responsive Delivery

The iScience review (Feng and Wang, 2022) showed that CS-GO delivery systems are most commonly fabricated as nanoparticles and hydrogels. In nanoparticles, GO provides a high-area aromatic loading platform, whereas chitosan improves aqueous dispersibility, biocompatibility, cellular interaction, and pH responsiveness. Covalent grafting is widely used when colloidal stability is required, while electrostatic assembly can preserve reversible response. Quantitative examples demonstrate that interface engineering can materially change loading and release: Abbasian *et al.* reported 93.8% drug loading and 78.6% encapsulation efficiency for a CS-g-PMAA/GO doxorubicin

nanosystem (Abbasian *et al.* 2018), while a pectin-coated CS-GO DsiRNA carrier achieved $92.6 \pm 3.9\%$ entrapment efficiency and selectively inhibited colon-cancer cells through VEGF-directed RNA interference (Katas *et al.* 2017).

Targeting functions have been introduced by charge reversal, receptor ligands, and magnetic phases. The GON/CS/CS-DMMA hybrid of Zhao *et al.* was designed to remain negatively charged and stable at physiological pH but become positively charged in the mildly acidic tumor extracellular environment, thereby promoting cellular uptake (Zhao *et al.* 2018). Galactosylated chitosan/GO/DOX nanoparticles increased hepatic-tumor-cell uptake and showed improved *in vivo* tumor localization and inhibition compared with non-galactosylated CS/GO/DOX (Wang *et al.* 2018). These studies support the value of active targeting, but formulation-specific pharmacokinetics, long-term biodistribution, and clearance remain essential translational gaps.

9.1.2 Hydrogel Carriers and Multi-responsive Release

Hydrogels add injectability, local retention, and stimulus-responsive transport to the loading capacity of GO. Rasoulzadehzali and Namazi incorporated Ag-decorated GO into chitosan hydrogel beads to combine pH-sensitive doxorubicin delivery with activity against both Gram-positive and Gram-negative bacteria (Rasoulzadehzali and Namazi, 2018). In CS/tripolyphosphate/GO hydrogel beads, increasing GO content slowed drug release, demonstrating that nanosheet content can be used as a diffusion-control parameter (Jafari *et al.* 2020). Zhao *et al.* further demonstrated coupled pH- and glucose-responsive

release in cationic chitosan/GO-BSA hydrogels (Zhao *et al.* 2017). In a glioblastoma model, a thermosensitive targeted chitosan/GO hydrogel co-delivering CPT-11 and SLP2 shRNA reduced xenograft tumor size to about 40% of the untreated control after 12 days (Lu *et al.* 2020).

Overall, nanoparticles provide the highest loading flexibility and can be engineered for active targeting, whereas hydrogels provide local retention, minimal invasiveness, and multi-responsive release. Across both forms, the most common weakness is the imbalance between sophisticated in vitro functionality and limited long-term in vivo evidence. Future comparisons should report dose-normalized loading, serum stability, release kinetics under physiologically relevant sink conditions, biodistribution, degradation,

and clearance rather than relying only on cumulative release curves (Feng and Wang, 2022; Rajput and Kanchandani, 2025).

Oral delivery provides another useful demonstration of prolonged release. Chitosan/GO bionanocomposite beads prepared by gelation loaded with metronidazole at 683 mg g⁻¹ and sustained release for up to 84 h in simulated gastric and intestinal media (Kumar *et al.* 2021). The release data were described using Korsmeyer–Peppas and first-order kinetics. This example is important because it links a simple bead format with high drug loading and an extended release window, but gastrointestinal stability, dose reproducibility, mucosal interactions, and in vivo pharmacokinetics still require validation before clinical translation.

Table 10. Detailed comparison of representative CS–GO drug and biomacromolecule delivery systems

System / Form	Payload or Design Feature	Representative Quantitative Result	Evidence and Principal Limitation	Ref.
CS-g-PMAA/GO nanoparticle	DOX; pH-responsive PMAA segment	Drug loading 93.8%; encapsulation 78.6%	Strong in vitro loading/release evidence; in vivo validation limited	(Abbasian <i>et al.</i> 2018)
GON/CS/CS-DMMA nanoparticle	DOX; tumor-pH charge reversal	Surface-charge reversal between physiological and mildly acidic tumor conditions	Improved uptake concept; formulation-specific biodistribution needed	(Zhao <i>et al.</i> 2018)
CS–GO–DsiRNA–pectin nanoparticle	VEGF-targeting DsiRNA; colon targeting	Entrapment efficiency 92.6 ± 3.9%	Caco-2 growth inhibition; requires in vivo efficacy/safety confirmation	(Katas <i>et al.</i> 2017)
Galactosylated CS/GO/DOX nanoparticle	Hepatic targeting via galactose	Higher tumor fluorescence and inhibition than CS/GO/DOX control	In vivo evidence available; quantitative pharmacokinetics remain limited	(Wang <i>et al.</i> 2018)
CS/GO-Ag hydrogel bead	DOX + antimicrobial Ag	pH-responsive release plus Gram-positive/Gram-negative antibacterial activity	Multifunctional; Ag and GO chronic safety require assessment	(Rasoulzadehzali and Namazi, 2018)
CS/TPP/GO hydrogel	Sumatriptan succinate	Higher GO fraction produced slower, more controlled release	Useful diffusion control; mainly in vitro evidence	(Jafari <i>et al.</i> 2020)
HTCC/GO-BSA hydrogel	Protein model; glucose-responsive design	Reduced burst release with dual pH/glucose response	Concept relevant to diabetes; therapeutic validation required	(Zhao <i>et al.</i> 2017)
Thermosensitive CS/GO targeted hydrogel	CPT-11 + SLP2 shRNA	Tumor size ≈40% of untreated control at day 12	Nude-mouse xenograft evidence; route/dose-specific safety needed	(Lu <i>et al.</i> 2020)
Covalent GO–CS nanoparticle	Proanthocyanidins	≈20 wt% loading; 97% HEK293 survival at 500 µg mL ⁻¹	Improved compatibility vs raw extract; pharmacology not established	(Figuerola <i>et al.</i> 2020)
Chi/GO gelation beads	Metronidazole; oral extended-release design	Drug loading 683 mg g ⁻¹ ; sustained release up to 84 h	Simple carrier format and long release window; in vivo GI pharmacokinetics not established	(Kumar <i>et al.</i> 2021)

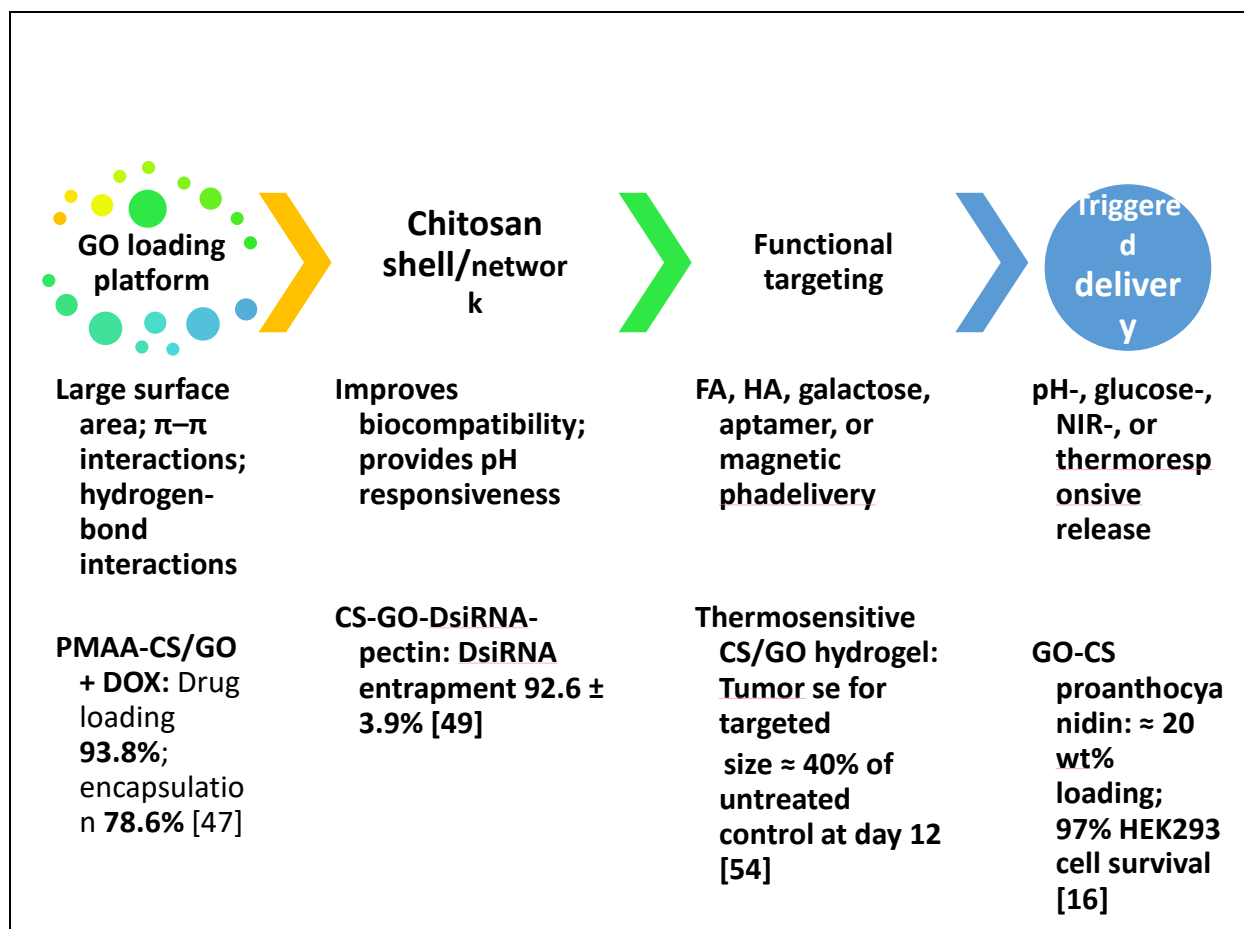


Fig. 12: Design logic and representative quantitative evidence for CS-GO drug and biomacromolecule delivery systems, original author synthesis based on Refs. (Feng and Wang, 2022; Figueroa *et al.* 2020; Abbasian *et al.* 2018; Zhao *et al.* 2018; Katas *et al.* 2017; Wang *et al.* 2018; Rasoulzadehzali and Namazi, 2018; Jafari *et al.* 2020; Zhao *et al.* 2017; Lu *et al.* 2020)

9.2 Wound Dressings

An effective wound dressing should control moisture, protect against bacteria, absorb exudate, permit gas exchange, minimize adhesion trauma, and support cell migration. Chitosan contributes hemostatic, antimicrobial, and film-forming properties, while GO reinforces the matrix and can provide antibacterial and photothermal functions. CS-GO has been processed into films, hydrogels, polyurethane composites, and electrospun nanofibers. Nanofibers offer high surface area and porosity; hydrogels absorb exudate and conform to irregular wounds; films provide a bacterial barrier but may trap exudate.

Recent biomedical studies and reviews describe CS-GO wound-dressing systems containing PVA, PVP, PEO, gelatin, bacterial cellulose, polyurethane, PLA/PLGA, Ag nanoparticles, and chemically modified GO. Reported benefits include improved tensile integrity, controlled water transport, enhanced antimicrobial activity, cytocompatibility, and accelerated wound closure (Feng and Wang, 2022; Moradi *et al.* 2021; Najafabadi *et al.* 2020; Mahmoudi *et al.* 2017; Yang *et al.* 2018; Yang *et al.* 2019; Xue *et al.* 2019; Chen *et al.* 2020; Liang *et al.* 2019; Wang *et al.* 2021). However, sterilization compatibility, residual cross-linkers, batch variability, degradation products, and performance in chronic infected wounds remain insufficiently standardized.

9.2.1 Nanofibrous Membranes

9.2.1 Nanofibrous Membranes

Electrospun CS-GO nanofibrous membranes are attractive because their high surface area, porosity, and gas permeability resemble extracellular-matrix architecture. Chitosan is commonly blended with PVA, PVP, PEO, or related carrier polymers to overcome limited electrospinnability. Yang *et al.* showed that GO incorporation into CS/PVA fibers improved hydrophilicity and generated antibacterial activity against *E. coli* and *S. aureus* (Yang *et al.* 2018). Antibiotic-loaded CS/PVA/GO fibers further combine sustained release with enhanced bacterial inhibition (Yang *et al.* 2019). In preclinical work, GO-containing chitosan/PVP temporary skin grafts were reported to accelerate wound healing by approximately 92%, with minimal visible scarring 14–21 days after treatment (Mahmoudi *et al.* 2017).

9.2.2 Films and Hydrogels

Films offer a strong bacterial barrier, whereas hydrogels are better suited to exudate management and irregular wound surfaces. Hierarchical GO–CS–calcium-silicate films achieved a tensile strength of about 10 MPa while providing breathability, water uptake, photothermal antibacterial activity, and in vivo wound-healing capability (Xue *et al.* 2019). A PVA/CS film containing 0.5 wt% modified GO showed an antibacterial rate about 50% higher than the GO control; wound

healing was reported to be about 41% faster than the untreated control and 31% faster than the PVA/CS dressing (Chen *et al.* 2020). For hydrogels, ZnO quantum-dot-modified GO–CS reached antibacterial efficiencies of 98.90% against *S. aureus* and 99.50% against *E. coli* (Liang *et al.* 2019), while a covalently grafted CS–GO hydrogel achieved a 92.2% wound-closure rate after 21 days and increased tensile stress and strain by approximately 2.1- and 1.2-fold compared with the corresponding noncovalent CS–GO hydrogel (Wang *et al.* 2021).

Table 11. Comparison of representative CS–GO wound-dressing systems and quantitative outcomes

Format / System	Key Design Feature	Representative Outcome	Main Strength / Limitation	Ref.
CS/PVP/GO nanofibrous mat	Electrospun temporary skin graft	≈92% wound-healing response; no obvious scar reported after 14–21 d	ECM-like porous structure; electrospinning complexity	(Mahmoudi <i>et al.</i> 2017)
CS/PVA/GO nanofiber	GO-assisted antibacterial nanofiber	Improved hydrophilicity and inhibition of <i>E. coli</i> and <i>S. aureus</i>	High surface area; carrier polymer needed for spinning	(Yang <i>et al.</i> 2018)
CS/PVA/GO + ciprofloxacin nanofiber	Antibiotic loading + GO adsorption	Sustained release with markedly enhanced bacterial inhibition	High efficacy; antibiotic-resistance stewardship required	(Yang <i>et al.</i> 2019)
GO–CS–CAS hierarchical film	Porous layered film	Tensile strength ≈10 MPa; photothermal antibacterial/wound-healing activity	Barrier + strength; film can retain exudate	(Xue <i>et al.</i> 2019)
PVA/CS/modified-GO film	PHMG-modified GO, 0.5 wt%	≈50% higher antibacterial rate vs GO; healing ≈41% faster than control	Strong antibacterial response; additive safety must be assessed	(Chen <i>et al.</i> 2020)
ZnO QD@GO–CS hydrogel	Photothermal + ROS + Zn ²⁺ antibacterial action	98.90% <i>S. aureus</i> and 99.50% <i>E. coli</i> antibacterial efficiency	Broad-spectrum killing; nanoparticle toxicity/leaching concerns	(Liang <i>et al.</i> 2019)
CS–CGO hydrogel	Covalently grafted GO network	92.2% wound closure at day 21; tensile stress 2.1× and strain 1.2× CS–GO	Improved mechanics and healing; degradation matching remains important	(Wang <i>et al.</i> 2021)
PU/CS–GO film	CS-modified GO in polyurethane matrix	Improved antibacterial wound-dressing performance	Robust film; biodegradability depends on polyurethane chemistry	(Najafabadi <i>et al.</i> 2020)

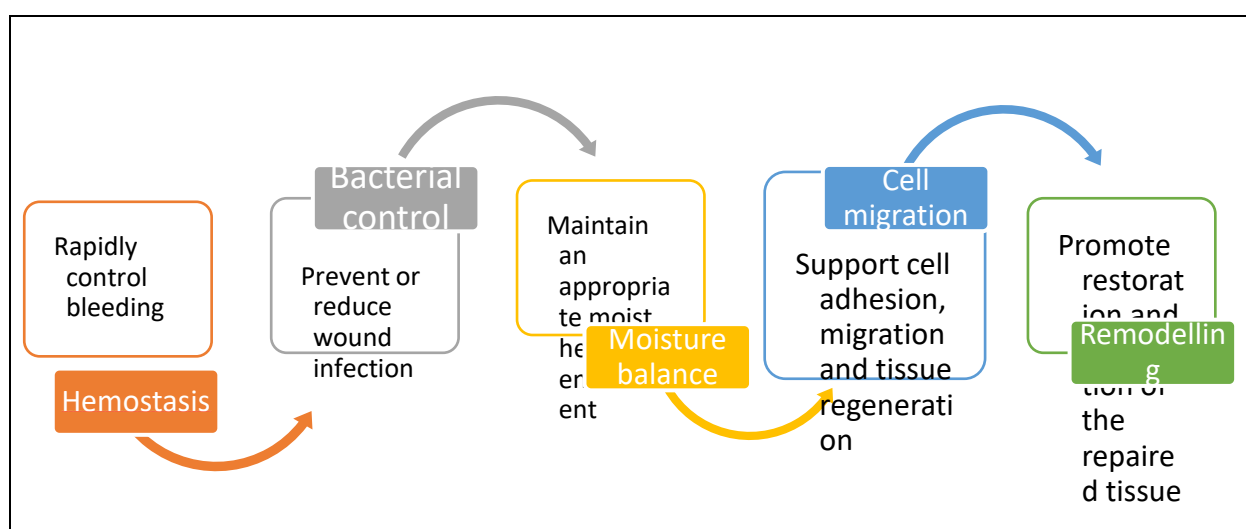


Fig. 13: Comparison of major CS–GO wound-dressing formats, their functional roles, and selected quantitative outcomes, original author synthesis based on Refs. (Najafabadi *et al.* 2020; Mahmoudi *et al.* 2017; Yang *et al.* 2018; Yang *et al.* 2019; Xue *et al.* 2019; Chen *et al.* 2020; Liang *et al.* 2019; Wang *et al.* 2021)

The cross-study pattern is consistent with the benchmark review (Feng and Wang, 2022): nanofibers maximize surface area and gas exchange, films provide a strong bacterial barrier, and hydrogels maximize exudate absorption and conformability. No single format optimizes all requirements. Translation therefore requires simultaneous control of antibacterial performance, mechanical integrity, moisture transport, hemostasis, sterilization resistance, degradation rate, and cytocompatibility rather than maximizing only one endpoint.

9.3 Bone and Cartilage Tissue Engineering

GO reinforces porous chitosan scaffolds, promotes protein adsorption, and can improve osteogenic cell attachment. Electrical and topographical cues may influence differentiation, while chitosan provides a

degradable extracellular-matrix-like environment. Three-dimensional scaffolds, aligned pores, hydrogels, beads, and hybrid structures containing hydroxyapatite, TiO₂, bioactive extracts, or growth factors have been investigated.

A CS/glutaraldehyde/GO/TiO₂/blackberry-waste-extract bead system was evaluated as a partial bone substitute in critical-size cranial defects. After 90 days, the study reported soft-tissue recovery, absence of necrotic areas or aggressive infection, and evidence of new bone formation by histology and elemental analysis (Valencia-Llano *et al.* 2021). Although promising, the multiple-component formulation makes it difficult to isolate the contribution of GO, and glutaraldehyde-related cytotoxicity and long-term degradation require careful assessment.

Table 12. Quantitative comparison of representative CS–GO systems for bone and cartilage tissue engineering

System	Structural / Bioactive Strategy	Representative Quantitative Result	Biological Interpretation / Limitation	Ref.
CS–GO porous scaffold	GO loading optimization	≈3 wt% GO associated with the highest osteogenic marker response in selected studies	Good osteogenic response; dose and oxidation state remain critical	(Dinescu <i>et al.</i> 2019; Hermenean <i>et al.</i> 2017)
GO/CS/gelatin scaffold	ECM-mimetic gelatin reinforcement	Bone-defect healing initiated as early as 2 weeks with collagen deposition	Promising in vivo evidence; composition-dependent degradation	(Saravanan <i>et al.</i> 2017)
SA–CS–Col–GO scaffold	Alginate/collagen + GO; optional Ca ²⁺ cross-linking	GO and Ca ²⁺ increased mechanical strength while preserving porous architecture	Improved cell proliferation; cross-linking did not automatically improve osteogenesis	(Kolanthai <i>et al.</i> 2018)
CMC/nHA/GO scaffold	nHA + GO surface engineering	Root-mean-square roughness ≈74.1 nm; enhanced osteoinductivity	Strong structure–cell signaling evidence; complex composition	(Yu <i>et al.</i> 2018)
CS/QCS/SrHA/GO scaffold	Strontium-substituted HA on GO	Compressive modulus 438.5 kPa (≈4× CS/QCS); week-12 bone density 0.83 vs 0.35 mg cm ^{−3} blank	Strong in vivo regeneration; multicomponent manufacturing complexity	(Wu <i>et al.</i> 2020)
Multilayer GO/CS/CAS	Brick-and-mortar / helical architecture	Flexural 137.2 MPa; compressive 80.2 MPa; toughness 1.46 MJ m ^{−3}	Near cortical-bone mechanical range; implantation required	(Xue <i>et al.</i> 2018)
CS/GP/GO thermoresponsive hydrogel	Injectable GO-reinforced thermogel	Upregulation of Runx2, ALP, COL-1 and OC	Minimally invasive; mechanical strength remains a limitation	(Saravanan <i>et al.</i> 2018)
nHA/GO/CS hydrogel	Self-assembled reinforced hydrogel	High-strength, oriented 3D hydrogel with improved HA fixation	Promising load support; processing/reduction chemistry must be controlled	(Yu <i>et al.</i> 2017)
nHA/GO/CS photothermal scaffold	30% nHA in GO-containing scaffold	Combined osteogenic differentiation and photothermal osteosarcoma treatment	Multifunctional; temperature and long-term safety require control	(Ma <i>et al.</i> 2020)

CS-GO Bone Tissue Engineering: Structure-Function-Outcomemap

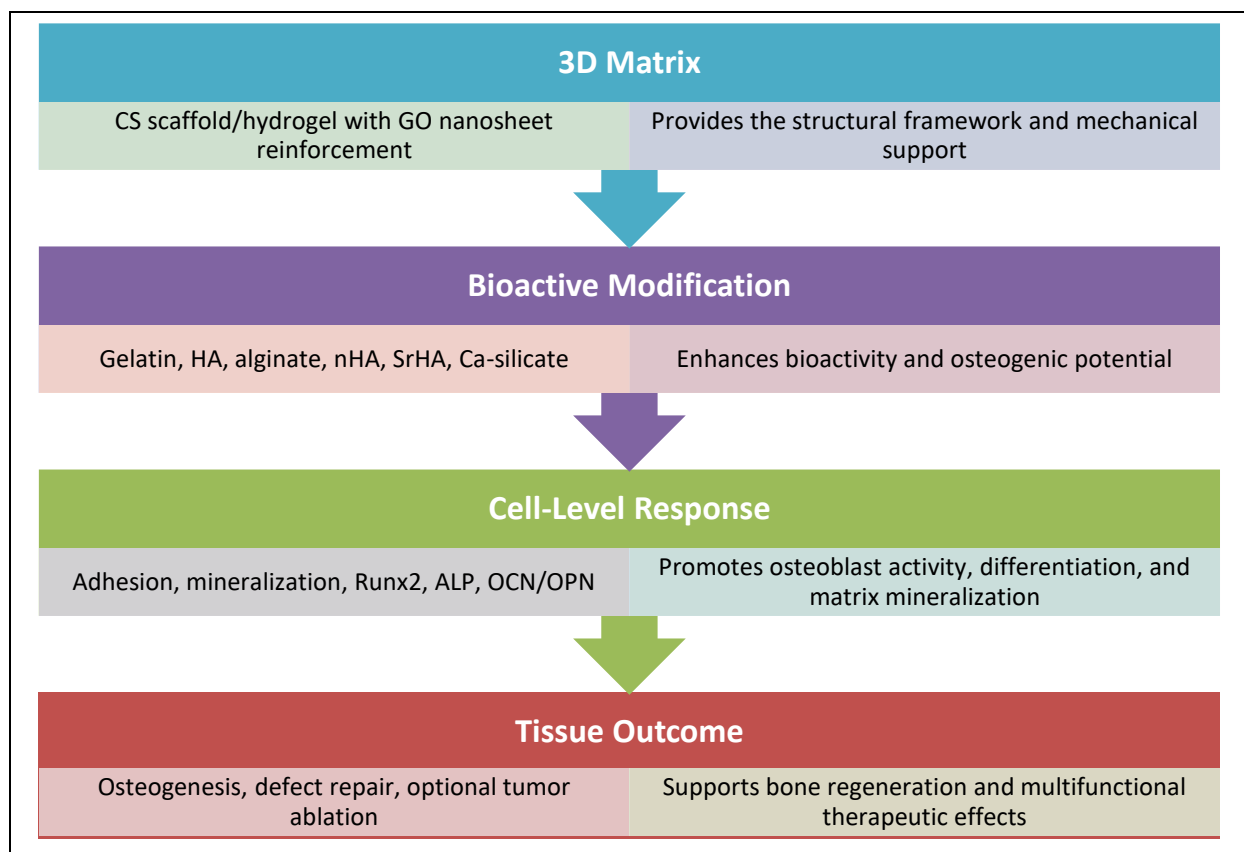


Fig. 14: Structure–function–outcome map for CS–GO bone-tissue engineering with representative mechanical and in vivo findings, original author synthesis based on Refs. (Dinescu *et al.* 2019; Ma *et al.* 2020; Hermenean *et al.* 2017; Saravanan *et al.* 2017; Kolanthai *et al.* 2018; Yu *et al.* 2018; Wu *et al.* 2020; Xue *et al.* 2018; Saravanan *et al.* 2018; Yu *et al.* 2017)

9.3.1 Porous Scaffolds and Bioactive Reinforcement

Porous CS–GO scaffolds are designed to mimic bone extracellular matrix and provide interconnected spaces for cell migration, vascular infiltration, mineralization, and new-tissue formation. Several studies identified a low-to-moderate GO range as optimal: chitosan–GO scaffolds containing about 3 wt% GO produced the strongest osteogenic-marker response in selected in vitro and in vivo comparisons (Dinescu *et al.* 2019; Hermenean *et al.* 2017), whereas excessive GO can reduce biosafety or cause aggregation. Adding gelatin, collagen, hyaluronic acid, alginate, hydroxyapatite, strontium-substituted hydroxyapatite, or calcium silicate further tunes mechanics and osteogenic cues (Saravanan *et al.* 2017; Kolanthai *et al.* 2018; Yu *et al.* 2018; Wu *et al.* 2020; Xue *et al.* 2018).

Quantitative studies show that architecture can be as important as chemistry. A CS/QCS/SrHA/GO scaffold reached a compressive modulus of 438.5 kPa, about four times that of CS/QCS, and produced a bone density of 0.83 mg cm⁻³ after 12 weeks compared with 0.35 mg cm⁻³ in the blank group (Wu *et al.* 2020). A multilayered GO/CS/calcium-silicate biomaterial designed to emulate cortical-bone organization achieved flexural strength of 137.2 MPa, compressive strength of

80.2 MPa, and toughness of 1.46 MJ m⁻³ (Xue *et al.* 2018). These values emphasize that nanosheet chemistry and hierarchical structure should be optimized together.

9.3.2 Injectable Hydrogels for Bone Regeneration

Hydrogels address irregular defects and permit minimally invasive injection but usually sacrifice load-bearing strength. Thermoresponsive CS/GP/GO hydrogels improved swelling, protein adsorption, biomineralization, and osteogenic differentiation, including upregulation of Runx2, ALP, COL-1, and osteocalcin (Saravanan *et al.* 2018). Self-assembled nHA/GO/CS hydrogels formed dense and oriented microstructures with improved mechanical integrity and hydroxyapatite fixation (Yu *et al.* 2017). The unresolved design challenge is therefore to combine injectability and defect conformity with sufficient mechanical stability for the intended anatomical site.

Taken together, the bone-regeneration literature supports a clear design rule: GO is most effective when used at an application-specific low or moderate loading within a porous, biologically active matrix rather than as a high-concentration filler. Future studies should report GO oxidation, sheet size, actual loading, pore-size distributions, mechanical properties under wet

conditions, degradation, and long-term in vivo fate so that promising osteogenic results can be compared reproducibly.

9.4 Antibacterial and Photothermal Systems

The antibacterial action of CS–GO systems is multifactorial. Protonated chitosan can interact with negatively charged microbial surfaces, alter permeability, and chelate essential nutrients. GO edges can physically disrupt membranes and contribute to oxidative stress. Adding Ag nanoparticles produces silver-ion release, membrane damage, protein/DNA binding, ROS generation, and biofilm inhibition. A green/pulsed-laser-ablation CS–GO–Ag nanocomposite showed enhanced broad-spectrum antibacterial activity relative to individual components; XRD indicated an average crystallite size near 30 nm and FE-SEM showed heterogeneous particles from approximately 32 to 175 nm (Naser *et al.* 2025).

9.5 Biosensors and Diagnostic Devices

GO provides high surface area, fluorescence quenching, and electrochemical transduction, while chitosan immobilizes enzymes, antibodies, nucleic acids,

or recognition molecules. Reported examples include glucose-oxidase/CS/GO nanofibers and phenylalanine-responsive fluorescent films for fish-freshness assessment. Sensor performance depends on biomolecule orientation, electron transfer, nonspecific adsorption, film swelling, and storage stability. Reduced GO or conductive additives may be required where electron transport through insulating chitosan is limiting.

Analytical performance can span several orders of magnitude depending on the recognition element and transduction mechanism. A fluorescence-resonance-energy-transfer glucose sensor using chitosan-modified GO produced a linear range of 0.1–1 mg mL⁻¹ and a detection limit of 0.05 mg mL⁻¹ (Li *et al.* 2019). For nucleic-acid detection, a GO/CS-modified glassy-carbon electrode detected *E. coli* O157:H7 target DNA over 1.0×10^{-14} to 1.0×10^{-8} M with a reported detection limit of 3.584×10^{-15} M (Xu *et al.* 2017). A DNA/Au–Pt bimetallic nanoparticle/GO–CS pencil-graphite platform measured zidovudine from 0.01 pM to 10 nM with a detection limit of 0.003 pM and was applied to human serum samples (Akbari *et al.* 2021). Enzyme-based platforms have also been reported for glucose and HbA1c-related biomarkers (Mehdizadeh *et al.* 2020; Shahbazmohammadi *et al.* 2020).

Table 13. Comparison of representative CS–GO biosensor and diagnostic platforms

Analyte / Application	CS–GO Platform	Reported Analytical Performance	Key Advantage / Limitation	Ref.
Glucose	MBP-rPC fluorescence/FRET on GO–CS	Linear range 0.1–1 mg mL ⁻¹ ; LOD 0.05 mg mL ⁻¹	Simple optical readout; concentration units/matrix differ from electrochemical sensors	(Li <i>et al.</i> 2019)
Glucose	GOD/CS/GO electrospun nanofiber on GCE	Efficient glucose oxidation and facilitated electron transfer	High surface area; long-term enzyme stability must be verified	(Mehdizadeh <i>et al.</i> 2020)
<i>E. coli</i> O157:H7 DNA	ssDNA/GO/CS/GCE impedimetric biosensor	1.0×10^{-14} – 1.0×10^{-8} M; LOD 3.584×10^{-15} M	Very low reported LOD; requires rigorous specificity and matrix validation	(Xu, 2017)
Zidovudine	DNA/Au–Pt BNPs/GO–CS/PGE	0.01 pM–10 nM; LOD 0.003 pM	Sub-picomolar performance and serum application; multicomponent electrode complexity	(Akbari and Zarei, 2021)
HbA1c-related Fru-ValHis	FPOX enzyme on CS/GO/AuNP electrode	High sensitivity/selectivity demonstrated in real blood samples	Clinically relevant matrix; calibration and storage stability need standardization	(Shahbazmohammadi <i>et al.</i> 2020)
Fish freshness / phenylalanine	GO–CS catalytic fluorescent film	Non-destructive freshness grading	Useful packaging integration; food-matrix and shelf-life validation needed	(Fazial and Tan, 2021)

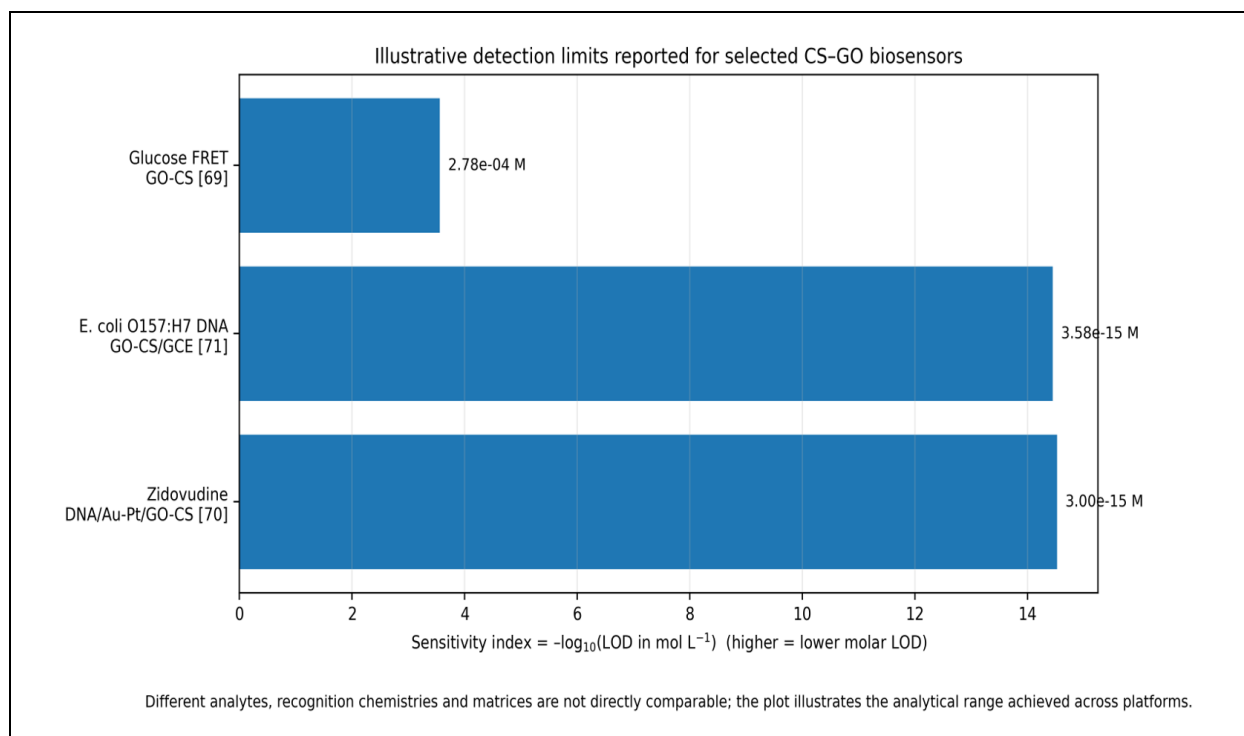


Fig. 15: Illustrative detection limits reported for selected CS–GO biosensors after conversion to molar units where possible, different analytes and recognition chemistries are not directly comparable (Li *et al.* 2019; Akbari *et al.* 2021; Xu, 2017)

For clinical and point-of-care use, very low detection limits alone are insufficient. Future CS–GO sensor studies should report calibration uncertainty, selectivity against clinically relevant interferents, matrix recovery, batch-to-batch electrode variation, storage stability, drift, fouling, and performance after sterilization or repeated bending where applicable. Conductive additives or partial GO reduction may improve electron transfer, but these changes must be reconciled with biocompatibility and green-processing goals (Feng and Wang, 2022; Mehdizadeh *et al.* 2020).

9.6 Blood-contact, Hemoperfusion, and Hemostatic Systems

The blood-contact interface is a distinct biomedical design problem because high adsorption must be achieved without excessive protein fouling, platelet activation, or hemolysis. A heparin-modified chitosan/GO hybrid hydrogel developed for bilirubin hemoperfusion reached a Langmuir maximum adsorption capacity of 92.59 mg g⁻¹ and successfully adsorbed bilirubin from enriched serum (Wei *et al.* 2015). Heparin modification reduced protein adsorption, platelet adhesion, and hemolysis and prolonged plasma clotting time from 4.1 to 23.6 min. These findings illustrate how GO-mediated mechanical and adsorptive enhancement can be coupled with a hemocompatible surface treatment. For translation, adsorption selectivity in whole blood, complement activation, sterilization stability, repeated-flow performance, and any GO or heparin release must be assessed.

9.7 Toxicity and Biocompatibility

GO biological effects vary with lateral size, thickness, oxidation, aggregation, dose, route, and protein corona. High concentrations have been associated with oxidative stress, hemolysis, inflammation, and reduced cell viability, while low doses or chitosan-coated GO can be substantially better tolerated. Prior biomedical reviews and toxicological studies indicate that chitosan coating can reduce GO hemolytic activity and that cytotoxicity often rises with GO concentration (Feng and Wang, 2022). Nevertheless, short-term cell viability is not sufficient evidence of safety. Long-term biodistribution, biodegradation, immunogenicity, genotoxicity, reproductive toxicity, and clearance must be assessed for each formulation.

9.8 Clinical Translation and Regulatory Considerations

Clinical translation of CS–GO systems requires more than short-term cell-viability data. For wound dressings, drug carriers and tissue scaffolds, regulatory evaluation would require reproducible composition, sterilization compatibility, extractables and leachable, endotoxin control, degradation products, hemocompatibility, immunogenicity, genotoxicity and application-route-specific *in vivo* evidence. FDA- or EMA-oriented development should identify whether the product is a device, drug, biologic or combination product, because the evidence package differs

substantially. In vivo studies should use clinically relevant doses and exposure routes and should track biodistribution, clearance, local inflammation, chronic toxicity and GO persistence. Toxicity mechanisms to monitor include oxidative stress, membrane disruption, complement activation, protein-corona formation, mitochondrial damage and inflammatory cytokine release. The form-specific evidence summarized above also indicates that each product class has a different translational bottleneck: systemic nanocarriers require pharmacokinetics and organ-clearance data; wound dressings require sterilization, extractables/leachables and chronic-wound models; bone scaffolds require degradation–regeneration matching and long-term implantation studies; and biosensors require matrix validation, calibration stability and manufacturable electrode architectures (Feng and Wang, 2022; Rajput and Khanchandani, 2025).

Table 14. Safety variables and recommended minimum reporting requirements

Risk Variable	Scientific Concern	Minimum Reporting Recommendation
GO concentration	Higher concentration can increase oxidative stress and cell loss	Report mass dose, surface-area dose and exposure time
Sheet size and edge density	Small sheets may cause stronger membrane/hemolytic effects	Report lateral-size distribution and thickness
Oxidation and defects	Control ROS generation, charge and protein adsorption	Report C/O ratio, Raman ID/IG and residual oxidants
Chitosan coating	Can reduce hemolysis and improve compatibility	Verify coating stability and GO release
Cross-linker residues	Glutaraldehyde and coupling reagents may dominate toxicity	Quantify residuals and washing efficiency
Application route	Inhalation, injection, skin contact and ingestion differ substantially	Use route-relevant models and chronic studies
Environmental release	Free nanosheets may affect aquatic organisms and microbial communities	Measure leaching, degradation products and end-of-life fate

10. FOOD PACKAGING AND AGRICULTURAL APPLICATIONS

Chitosan already has a strong basis for edible and active packaging because it forms oxygen-barrier films and exhibits antimicrobial activity. GO can increase

stiffness, tensile strength, thermal stability, UV shielding, and tortuosity, while reducing the amount of polymer required. Reduced GO may also introduce electrical conductivity for smart packaging. Potential applications include antimicrobial films, oxygen or humidity sensors, freshness indicators, and coatings for fruits, vegetables, meat, and seafood.

Quantitative hybrid-film data illustrate the potential of ternary reinforcement. In a chitosan/ZnO/GO food-packaging nanocomposite, the temperatures at 25% and 50% mass loss increased by 46.5 and 62.1 °C, respectively, and the maximum degradation temperature increased by 19 °C relative to neat chitosan [86]. Water-vapour permeability decreased from 2.22 to 1.04 g·mm m⁻² h⁻¹ kPa⁻¹, while the inhibition zone against *Bacillus subtilis* increased from 5 mm for neat chitosan to 12 mm for the hybrid. Such ternary systems demonstrate simultaneous thermal, barrier, and antimicrobial enhancement, but food-contact migration, nanoparticle release, optical/sensory acceptance, and end-of-life behavior remain decisive constraints.

Translation to food contact requires particular caution. GO migration into food simulants, effects of particle size and oxidation, interactions with acidic or fatty foods, oral toxicity, and environmental release during disposal must be quantified. Optical transparency and color may limit acceptable loading. Regulatory approval will require reproducible composition, migration below relevant limits, and evidence that antimicrobial performance does not encourage inappropriate extension of unsafe shelf life.

Food-contact use also requires migration studies in standard food simulants, including aqueous, acidic, alcoholic and fatty conditions. Migration limits depend on the regulatory region and on whether the material is intended as a direct food-contact film, coating, active package or intelligent sensor. Shelf-life studies should measure microbial load, oxidation, water-vapour and oxygen transmission, mechanical integrity, colour/opacity, sensory acceptance and nanoparticle release during storage. At present, most CS–GO food-packaging studies remain laboratory demonstrations rather than commercial products; commercial implementation will require scale-compatible film formation, sealing behaviour, printability, compostability or recyclability data, and permission for all food-contact components.

11. FLEXIBLE ELECTRONICS, ENERGY, AND SMART MATERIALS

CS–GO nanocomposites can function as flexible dielectric layers, proton-conducting membranes, humidity-responsive materials, electrodes after reduction, and matrices for supercapacitor or battery components. Chitosan contributes flexibility and ionic

conduction, while GO or rGO contributes dielectric polarization and electronic transport. The reported bias-dependent reversible reduction and negative capacitance tunability in humid CS–GO films suggests gate dielectrics and sensors (Prokhorov and Luna-Bárceñas, 2020). Yet moisture sensitivity, hysteresis, long-term bias stability, and reproducible partial reduction remain important device-engineering challenges.

In wearable and printed electronics, CS–GO materials may serve as flexible substrates, humidity sensors, strain-sensitive layers, electrochemical biosensor matrices, biodegradable dielectric films and smart-packaging indicators. Printable inks require stable dispersion, suitable viscosity, substrate adhesion and low-temperature drying. Wearable devices require flexibility, skin compatibility, sweat stability, cyclic bending durability and signal stability under humidity

changes. Commercial use is still limited because unreduced GO has poor conductivity, while chemical reduction can reduce biodegradability or introduce residual reagents. Practical device development should therefore combine green reduction, encapsulation, long-cycle reliability testing and end-of-life recovery strategies.

Energy-storage applications generally require higher conductivity than unreduced GO provides. Strategies include chemical, thermal, electrochemical, or green reduction; hybridization with conducting polymers; and addition of metal oxides. These modifications can compromise biodegradability or introduce toxic reagents, so an application-specific balance between conductivity, mechanical flexibility, safety, and environmental footprint is necessary.

Environmental Remediation	Biomedical	Food & Agriculture	Smart Materials & Devices
Metal-ion removal; dye removal; PFAS treatment; membrane applications; magnetic adsorbents; regeneration and real-matrix treatment	Drug delivery; wound healing; bone/tissue engineering; biosensors; photothermal applications	Active/antimicrobial packaging; barrier and UV protection; freshness indicators	Flexible dielectrics; sensors; humidity/protonic response; energy-related hybrid materials

Fig. 16: Cross-domain application landscape of CS–GO nanocomposites. Original author synthesis integrating environmental, biomedical, food-packaging, and smart-material uses

11.1 Smart Sensing and Protective Coatings

Recent CS–GO sensing studies show that the same oxygenated interface responsible for hydration and adsorption can be exploited for transduction. A drop-cast GO–CS humidity sensor reported high sensitivity, rapid response/recovery, low hysteresis, and good repeatability, with performance optimized by composite ratio (Kumari *et al.* 2025). A QCM sensor based on a porous GO/CS nanofiber network detected methylamine, dimethylamine, and trimethylamine with sensitivities of 2.7, 2.3, and 4.8 Hz ppm⁻¹, respectively, and limits of detection below 3 ppm (Zhang *et al.* 2017). These examples support CS–GO as a low-cost platform for humidity, freshness, and volatile-amine monitoring, but selectivity, baseline drift, cyclic humidity exposure, and calibration stability must be reported under real operating conditions.

Protective coatings exploit a related barrier mechanism. Oleic-acid-grafted CS/GO increased the corrosion resistance of a carbon-steel coating by approximately 100-fold relative to pristine chitosan, attributed to improved hydrophobicity and delayed

penetration of corrosive species (Fayyad *et al.* 2016). A GO–CS–ZnO ternary nanohybrid achieved 85.61% corrosion inhibition at 500 ppm, compared with 83.81% for GO–CS and 42.35% for GO alone (Majidi *et al.* 2020). These results indicate that interface chemistry and tortuous diffusion paths can translate CS–GO from passive films into multifunctional protective surfaces; however, coating adhesion, abrasion resistance, weathering, nanoparticle leaching, and reparability require long-duration testing.

11.2 Energy Storage and Conversion

For proton-exchange membranes, chemically functionalized GO can create acid–base pairs and proton-hopping pathways within chitosan. Phosphorylated GO increased anhydrous conductivity from 0.25 to 5.79 mS cm⁻¹ at 160 °C and 0% relative humidity, a 22.2-fold enhancement (Bai *et al.* 2015). In a complementary strategy, combined sulfonated chitosan and sulfonated GO increased proton conductivity by 454%, reduced methanol permeability by 23%, and increased membrane selectivity by 650% relative to neat chitosan at 5 wt% SGO (Shirdast *et al.* 2016). These results demonstrate

that chemical functionalization can overcome the low intrinsic proton conductivity of chitosan, although synthesis burden, acid retention, durability, and comparison with commercial membranes must be considered.

Supercapacitor studies similarly use rGO or porous GO to provide conductive pathways while chitosan contributes processability and heteroatom-rich surface chemistry. A $\text{Fe}_3\text{O}_4/\text{GO}/\text{chitosan}$ aerogel delivered approximately 160 F g^{-1} , 14.6 Wh kg^{-1} and 0.77 kW kg^{-1} in a neutral electrolyte, with about 91% coulombic efficiency after 10,000 cycles (Chadha *et al.* 2022). A modified-chitosan/holey-GO hydrogel electrode reached 377 F g^{-1} at 5 A g^{-1} ; a flexible solid-state device based on the material delivered 210 F g^{-1} at 0.5 A g^{-1} and 31 Wh kg^{-1} at 150 W kg^{-1} (Jiang *et al.* 2023). These data highlight the role of hierarchical pores, wettability, and shortened ion-diffusion pathways, while also showing why cycling stability, device-level mass loading, and green reduction routes must be evaluated together.

CS-rGO can also act as a support for energy-conversion catalysts. Pd nanoparticles encapsulated within CS-rGO achieved a turnover frequency of $42.5 \text{ mol H}_2 \text{ mol Pd}^{-1} \text{ min}^{-1}$ for ammonia-borane hydrolysis, with an activation energy of $39.02 \text{ kJ mol}^{-1}$ and stable

hydrogen-generation activity over four runs (Liu *et al.* 2019). Although this is not a direct electrical-storage application, it illustrates the broader role of CS-GO interfaces in stabilizing active nanoparticles and facilitating mass transfer for hydrogen-related catalysis.

CS-GO Interfacial design to Smart Sensing and Energy Applications.

12.1 Cross-study Interpretation of Quantitative Evidence

The numerical values assembled in this review demonstrate achievable performance but are not universal material constants. Adsorption capacity depends on pH, ionic strength, initial concentration, dose, equilibrium criteria, and isotherm selection. Mechanical properties depend on chitosan degree of deacetylation and molecular weight, GO lateral dimensions and oxidation, moisture conditioning, specimen thickness, and strain rate. Drug-loading and release percentages depend on payload chemistry, sink conditions, assay method, and the definition of loading efficiency. Accordingly, within-study controls provide the strongest evidence, whereas cross-study graphs are best used to identify design trends.

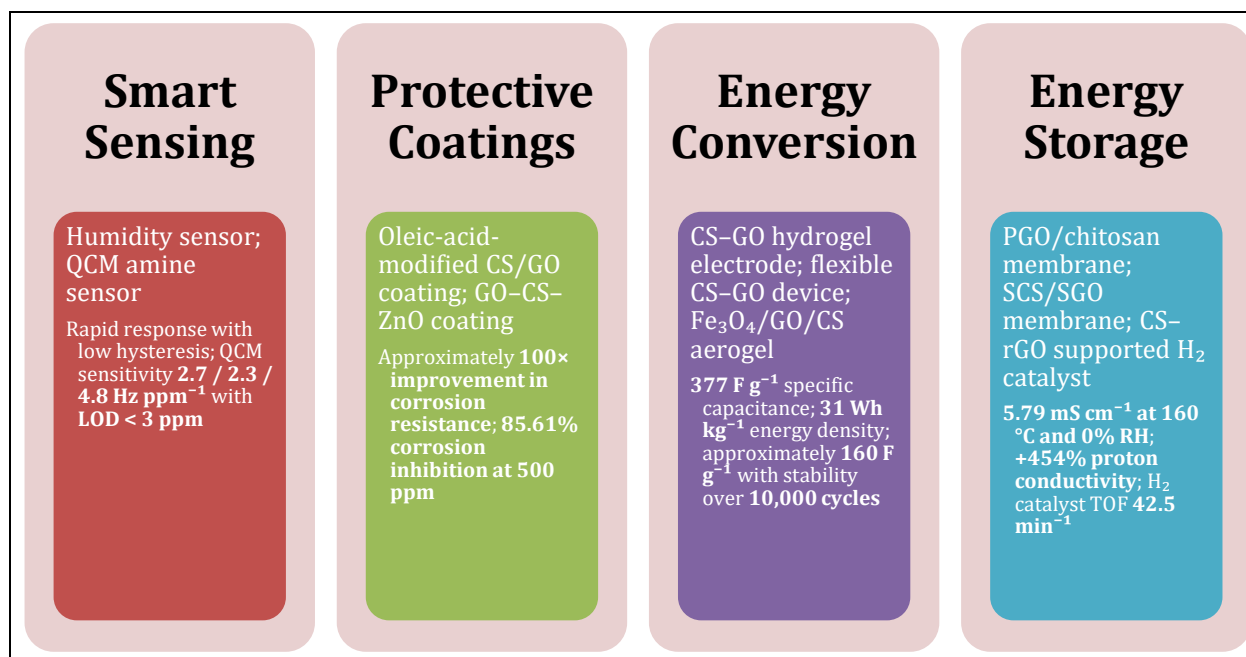


Fig. 17(a): Interface-to-function map for CS-GO smart sensing, protective coatings, energy storage, proton-exchange membranes, and hydrogen-generation catalysis; representative study-specific values are drawn from Refs. (Bai *et al.* 2015; Chadha *et al.* 2022; Jiang *et al.* 2023; Shirdast *et al.* 2016; Liu *et al.* 2019; Kumari *et al.* 2025; Zhang *et al.* 2017; Fayyad *et al.* 2016; Majidi *et al.* 2020)



Fig. 17(b): Interface-to-function map for CS–GO smart sensing, protective coatings, energy storage, proton-exchange membranes, and hydrogen-generation catalysis; representative study-specific values are drawn from Refs. (Bai *et al.* 2015; Chadha *et al.* 2022; Jiang *et al.* 2023; Shirdast *et al.* 2016; Liu *et al.* 2019; Kumari *et al.* 2025; Zhang *et al.* 2017; Fayyad *et al.* 2016; Majidi *et al.* 2020)

Table 15. Quantitative comparison of representative CS–GO smart-material and energy-conversion systems

System / Application	Design Feature	Representative Performance	Translation / Sustainability Issue	Ref.
PGO/CS proton-exchange membrane	Phosphorylated GO proton-hopping sites	5.79 mS cm ⁻¹ at 160 °C, 0% RH; 22.2× increase	Functionalization burden; acid retention and durability	(Bai <i>et al.</i> 2015)
Fe ₃ O ₄ /GO/CS aerogel supercapacitor	3D porous magnetic hybrid	~160 F g ⁻¹ ; ~14.6 Wh kg ⁻¹ ; ~0.77 kW kg ⁻¹ ; ~91% coulombic efficiency after 10,000 cycles	Scale-up of hydrothermal/aerogel processing	(Chadha <i>et al.</i> 2022)
Modified-CS / holey-GO hydrogel	Hierarchical pores and conductive network	377 F g ⁻¹ at 5 A g ⁻¹ ; flexible device 31 Wh kg ⁻¹ at 150 W kg ⁻¹	Device-level loading and long-term mechanical reliability	(Jiang <i>et al.</i> 2023)
SCS/SGO/CS fuel-cell membrane	Sulfonated polymer + GO ionic domains	+454% proton conductivity; ~23% methanol permeability; +650% selectivity	Chemical functionalization and benchmarking against commercial PEMs	(Shirdast <i>et al.</i> 2016)
Pd/CS–rGO catalyst	Pd nanoparticles stabilized in CS–rGO	TOF 42.5 mol H ₂ mol Pd ⁻¹ min ⁻¹ ; Ea 39.02 kJ mol ⁻¹ ; stable 4 runs	Precious-metal recovery and catalyst life-cycle burden	(Liu <i>et al.</i> 2019)
GO–CS humidity sensor	Drop-cast hydrophilic sensing layer	High sensitivity, rapid response/recovery, low hysteresis	Drift, calibration and cyclic humidity stability	(Kumari <i>et al.</i> 2025)
GO/CS QCM amine sensor	Porous nanofiber sorption layer	MA/DMA/TMA: 2.7/2.3/4.8 Hz ppm ⁻¹ ; LOD <3 ppm	Interferents and real-headspace validation	(Zhang <i>et al.</i> 2017)
Oleic-acid CS/GO coating	Hydrophobic tortuous barrier	~100× corrosion resistance vs pure CS	Weathering, adhesion and coating repairability	(Fayyad <i>et al.</i> 2016)
GO–CS–ZnO corrosion inhibitor	Ternary adsorption/barrier hybrid	85.61% inhibition at 500 ppm	Nanoparticle leaching and long-term exposure	(Majidi <i>et al.</i> 2020)

12. COMPARATIVE APPLICATION SUMMARY

Table 16. Cross-application comparison of CS–GO formats, mechanisms, outcomes, and limitations

Application	Representative CS–GO Format	Key Mechanism	Selected Reported Outcome	Primary Limitation	References
Mechanical reinforcement	Solution-cast CS/GO film	Interfacial load transfer and sheet reinforcement	1 wt% GO: tensile strength +122%; Young's modulus +64%	Aggregation and brittleness above optimum loading	(Prokhorov and Luna-Bárcenas, 2020; Valencia-Llano <i>et al.</i> 2021; Figueroa <i>et al.</i> 2020)
Cationic dye removal	Cross-linked GO–chitosan film	π – π stacking, electrostatics, hydrogen bonding	Methylene blue Qm 402.6 mg g ⁻¹ vs 286.9 mg g ⁻¹ for GO	Regenerant waste and real-effluent competition	(Khandegar <i>et al.</i> 2021; Sabzevari <i>et al.</i> 2018; Prokhorov and Luna-Bárcenas, 2020; Vo <i>et al.</i> 2024; Ahmed <i>et al.</i> 2023; Valencia-Llano <i>et al.</i> 2021)
E-waste metal removal	GO–CS biosorbent	pH-dependent coordination, HSAB selectivity	Cu 99.98%, Co 92.55%, Ni 72.36% under different optima	Different optimum pH/time for each metal	(Promkatkaew <i>et al.</i> 2025; Sabzevari <i>et al.</i> 2018; Prokhorov and Luna-Bárcenas, 2020)
Pb(II) removal	Fe ₃ O ₄ /GO/CS magnetic nanosorbent	Chelation plus magnetic recovery	q _{max} 63.45 mg g ⁻¹ ; ~12% loss after 4 cycles	Magnetic nanoparticle leaching/pore blocking	(Khandegar <i>et al.</i> 2021; Sabzevari <i>et al.</i> 2018; Prokhorov and Luna-Bárcenas, 2020; Vo <i>et al.</i> 2024; Ahmed <i>et al.</i> 2023; Valencia-Llano <i>et al.</i> 2021)
Dye removal	CuFe ₂ O ₄ /CS/GO magnetic composite	Electrostatic and π interactions; magnetic separation	112.6 mg g ⁻¹ IC; 66.15 mg g ⁻¹ SAF; 5-cycle reuse	Multicomponent synthesis and disposal	(Khandegar <i>et al.</i> 2021; Sabzevari <i>et al.</i> 2018; Prokhorov and Luna-Bárcenas, 2020; Vo <i>et al.</i> 2024; Ahmed <i>et al.</i> 2023; Valencia-Llano <i>et al.</i> 2021)
Phytodrug delivery	Covalent GO–CS nanoparticles	π – π /hydrophilic loading and sustained release	~20 wt% loading; 97% cell survival for loaded system	In vivo pharmacology not established	(Khandegar <i>et al.</i> 2021; Moradi <i>et al.</i> 2021; Figueroa <i>et al.</i> 2020; Su <i>et al.</i> 2021; Valencia-Llano <i>et al.</i> 2021; Naser <i>et al.</i> 2025; Ali <i>et al.</i> 2023)
Multidrug/photothermal	CS/AgNP/GO composite	pH response, Ag antimicrobial action, NIR heating	Dual release, <i>E. coli</i> / <i>S. aureus</i> inhibition, photothermal conversion	Silver/GO long-term toxicity	(Khandegar <i>et al.</i> 2021; Moradi <i>et al.</i> 2021; Figueroa <i>et al.</i> 2020; Su <i>et al.</i> 2021; Valencia-Llano <i>et al.</i> 2021; Naser <i>et al.</i> 2025; Ali <i>et al.</i> 2023)
Bone regeneration	CS/GO/TiO ₂ /plant-extract beads	Mechanical support and osteogenic microenvironment	Evidence of new bone after	Attribution among multiple components	(Khandegar <i>et al.</i> 2021; Moradi <i>et al.</i> 2021; Figueroa <i>et al.</i> 2021)

			90 days in critical defects		<i>al.</i> 2020; Su <i>et al.</i> 2021; Valencia-Llano <i>et al.</i> 2021; Naser <i>et al.</i> 2025; Ali <i>et al.</i> 2023)
Antibacterial material	CS–GO–Ag nanocomposite	Membrane disruption, ROS, Ag ⁺ release	Enhanced broad-spectrum activity	Particle size heterogeneity and migration	(Khandegar <i>et al.</i> 2021; Moradi <i>et al.</i> 2020; Figuerola <i>et al.</i> 2020; Su <i>et al.</i> 2021; Valencia-Llano <i>et al.</i> 2021; Naser <i>et al.</i> 2025; Ali <i>et al.</i> 2023)
Flexible electronics	CS–GO film	Protonic/electronic polarization and reversible reduction	Dielectric constant increased and resistivity decreased with DC bias	Humidity dependence and hysteresis	(Promkatkaew <i>et al.</i> 2025; Prokhorov and Luna-Bárceñas, 2020)
Microplastic remediation	NH ₂ –MIL-101(Fe)/CS/GO	Electrostatic + hydrophobic + π interactions	PET/PS removal 93.8%/89.7%; six-cycle reuse	MOF/nanoparticle stability in real wastewater	(Yakout <i>et al.</i> 2026)
High-salinity desalination	CS/GO mixed-matrix membrane	Hydrophilic transport + dense selective matrix	30.0 kg m ⁻² h ⁻¹ ; 99.99% NaCl rejection	Thermal energy, swelling and fouling	(Qian <i>et al.</i> 2018)
Flexible supercapacitor	Modified-CS / holey-GO hydrogel	Hierarchical porosity + conductive network	377 F g ⁻¹ ; device energy density 31 Wh kg ⁻¹	Scale-up and long-cycle mechanical reliability	(Jiang <i>et al.</i> 2023)
Blood detoxification	Heparin-modified CS/GO hydrogel	Bilirubin adsorption + hemocompatible surface	q _{max} 92.59 mg g ⁻¹ ; clotting time 4.1→23.6 min	Whole-blood selectivity and chronic blood-contact safety	(Wei <i>et al.</i> 2015)

13. CHALLENGES AND KNOWLEDGE GAPS

13.1 Material Variability and Incomplete Reporting

The term ‘graphene oxide’ covers materials with widely different oxidation levels, lateral dimensions, thicknesses, residual metals, and defect densities. Chitosan likewise varies in DD, molecular weight, source, acetylation pattern, and purity. Many papers omit one or more of these descriptors. As a result, nominally identical CS/GO ratios can produce different dispersion, charge, mechanics, and toxicity. Minimum reporting standards should include carbon-to-oxygen ratio, lateral size distribution, layer number, zeta potential, residual oxidants/metals, chitosan DD and molecular weight, actual—not nominal—composite composition, moisture content, and residual cross-linker.

13.2 Reproducibility and Test Standardization

Mechanical, adsorption, antimicrobial, release, and biological data are strongly protocol-dependent.

Tensile results require consistent conditioning and geometry. Adsorption studies should provide mass balance, blank controls, equilibrium verification, realistic concentration ranges, competing ions, and desorption data. Antibacterial studies should separate bacteriostatic from bactericidal effects and quantify particle release. Drug-delivery studies need loading-state characterization, sink conditions, release-mechanism analysis, and comparison with free drug and carrier controls.

13.3 Toxicology and Environmental Release

Chitosan can improve GO compatibility but does not automatically eliminate risk. Covalent linkage, protein adsorption, degradation, sterilization, and mechanical wear can change exposure. Ternary systems containing Ag, TiO₂, ferrites, or other nanoparticles introduce additional hazards. Application-specific exposure scenarios are required: bloodstream, wound bed, oral food contact, inhalation during manufacture, or aquatic release from spent adsorbents.

Comparative maturity of evidence across CS-GO application domains					
	Quantitative performance	Mechanistic evidence	Real-matrix / in vivo evidence	Reuse / long-term stability	Scale-up / regulatory evidence
Water remediation	Stronger	Stronger	Developing	Developing	Limited
Drug delivery	Stronger	Stronger	Developing	Limited	Limited
Wound dressing	Developing	Developing	Developing	Limited	Limited
Bone/tissue engineering	Developing	Developing	Developing	Limited	Limited
Food packaging	Developing	Developing	Limited	Limited	Limited
Sensors & electronics	Developing	Developing	Limited	Limited	Limited

Fig. 18: Qualitative comparison of evidence maturity across CS–GO application domains. This author synthesis is not a meta-analysis and is based on Refs. (Moradi *et al.* 2021; Sabzevari *et al.* 2018; Promkatkaew *et al.* 2025; Prokhorov and Luna-Bárcenas, 2020; El-Sheikh *et al.* 2025; Vo *et al.* 2024; Ahmed *et al.* 2023; Figueroa *et al.* 2020; Su *et al.* 2021; Valencia-Llano *et al.* 2021; Naser *et al.* 2025; Ali *et al.* 2023; Dinescu *et al.* 2019; Emadi *et al.* 2017; Mehdizadeh *et al.* 2020; Fazial and Tan, 2021; Najafabadi *et al.* 2020; Mahmoudi *et al.* 2017; Francolini *et al.* 2019; Grande *et al.* 2017; Tran *et al.* 2017; Travlou *et al.* 2013; Bao *et al.* 2011; Ma *et al.* 2020; Ahmed *et al.* 2017; Croitoru *et al.* 2020; Liu *et al.* 2018; Adonis *et al.* 2026; Mahanty *et al.* 2026; Sun *et al.* 2026; Rajput and Khanchandani, 2025; Bai *et al.* 2015; Chadha *et al.* 2022; Jiang *et al.* 2023; Shirdast *et al.* 2016; Liu *et al.* 2019; Kumari *et al.* 2025; Zhang *et al.* 2017; Fayyad *et al.* 2016; Majidi *et al.* 2020; Bulin *et al.* 2025; Marnani and Shahbazi, 2019; Yakout *et al.* 2026; Wei *et al.* 2015; Kanted *et al.* 2023; Qian *et al.* 2018; Kumar *et al.* 2021)

13.4 Scale-up and Green Manufacturing

Modified Hummers oxidation uses concentrated acid and strong oxidants and generates washing effluent. Chitosan extraction can also consume large quantities of acid, alkali, heat, and water. A material should not be labelled sustainable solely because its polymer is bio-based. Greener graphite oxidation, electrochemical exfoliation, recovery of acid and permanganate, biological chitosan extraction, solvent recycling, low-energy drying, and waste-derived feedstocks should be compared by life-cycle assessment.

The expanded evidence base also exposes a performance–sustainability trade-off. Some of the highest-performing CS–GO systems rely on extensive functionalization, metal or metal-oxide decoration, strong acids, high-temperature hydrothermal treatment, or cross-linkers and reducing agents that increase chemical and energy burdens. Green alternatives—including aqueous processing, genipin or tannic-acid cross-linking, ascorbic-acid or plant-derived reduction,

closed-loop reagent recovery, and low-temperature fabrication—should therefore be evaluated against conventional routes using functional-unit-based life-cycle assessment and techno-economic analysis rather than by the label ‘green’ alone. Performance per unit mass, service life, regeneration cycles, and end-of-life recovery should be included in such comparisons.

13.5 Device and Process Integration

Many studies demonstrate material performance in isolated tests but not in the intended system. Adsorbents require columns, pressure-drop analysis, separation, regeneration, and metal recovery. Wound dressings require sterilization, packaging, shelf stability, and animal or clinical testing. Sensors require calibration drift, selectivity, interferents, and device encapsulation. Packaging requires machinability, sealing, migration, food compatibility, and disposal. Future work should therefore move from material screening to integrated prototypes and application-relevant standards.



Fig. 19: Circularity-by-design framework for CS-GO nanocomposites, linking renewable feedstocks, green synthesis, interface/process control, functional use, recovery/reuse, and end-of-life management through life-cycle assessment (LCA), techno-economic analysis (TEA), and safe-by-design feedback

14. FUTURE RESEARCH DIRECTIONS

14.1 AI-assisted Materials Design, Life-cycle Assessment and Commercialization

AI-assisted materials discovery can accelerate CS-GO development by linking chitosan DD, molecular weight, GO size, oxidation level, filler loading, pH, cross-linking and processing variables with measured outputs such as adsorption capacity, tensile strength, cell viability, conductivity and degradation. However, machine-learning models will be useful only if datasets contain standardized descriptors, negative results, uncertainty values and comparable test protocols. Digital materials discovery should therefore be combined with design of experiments, automated literature extraction and open data repositories. Equally important, every claim of sustainability should be tested through life-cycle assessment, techno-economic analysis and circular-economy metrics. Commercialization barriers include raw-material variability, GO synthesis cost, quality control, regulatory approval, nanoparticle migration, waste treatment, sterilization, shelf stability and competition with lower-cost conventional materials.

Future work should first establish a shared material passport for GO and chitosan that records oxidation state, sheet size and layer number, residual metals, chitosan degree of deacetylation and molecular weight, and the actual composite composition. Green and waste-derived production routes should then be evaluated by life-cycle and cost analysis rather than assumed to be sustainable. Standardized datasets can support design-of-experiments and machine-learning structure-property maps linking composition and processing with mechanical, adsorption, biological, and electrical performance. Low GO loadings and controlled nanosheet orientation should be optimized to maximize reinforcement and barrier effects while limiting aggregation, opacity, and toxicity.

For environmental systems, adsorbents should be evaluated in multicomponent real waters and continuous-flow configurations while reporting regeneration, contaminant recovery, nanoparticle leaching, and capacity retention. Recoverable formats such as beads, monoliths, magnetic particles, and supported membranes should be prioritized to reduce GO loss and enable repeated use. For biomedical systems, standardized hemocompatibility, immunotoxicity,

genotoxicity, degradation, biodistribution, and long-term in vivo studies at clinically relevant doses are needed.

Table 17. Priority research actions for translation of CS–GO nanocomposites

Priority	Recommended Research Action
Standardization	Report DD, molecular weight, GO lateral size/thickness, C/O ratio, dispersion protocol, composition and residual reagents.
Mechanistic characterization	Combine spectroscopy, microscopy, surface charge, molecular simulation and post-use analysis.
Real matrices	Move from single-solute laboratory water to competitive ions, natural organic matter, real effluent and continuous flow.
Regeneration and life cycle	Quantify capacity loss, desorption chemicals, energy demand, GO leakage and adsorbent end-of-life.
Biomedical translation	Use standardized hemocompatibility, immunogenicity, degradation and chronic in vivo protocols.
Smart systems	Develop stimuli-responsive release, self-healing electronics, multimodal sensors and AI-guided composition optimization.
Sustainable synthesis	Replace harsh GO oxidation and toxic cross-linkers; use waste-derived chitosan/graphitic carbon with life-cycle assessment.
Data-driven materials design	Create open datasets linking composition and processing to mechanical, adsorption, biological and electrical outcomes.

For food-packaging applications, future studies should quantify migration and oral exposure, include sensory studies, and evaluate compostability or recyclability of the complete composite. Translation should also progress toward demonstrator devices—including wound patches, packed-bed adsorbers, electrochemical sensors, and flexible transistors—with reliability assessed under realistic operation. Across all application classes, safe-by-design rules should be

defined for GO lateral size, oxidation state, surface coating, dose, and degradation products.

Table 18. Proposed minimum data package for future CS–GO publications

Category	Minimum Information
Raw materials	Chitosan source, DD, molecular weight; GO synthesis, C/O ratio, sheet size and thickness
Processing	Concentration, pH, sonication energy/time, mixing order, cross-linker ratio, drying/freeze-drying conditions
Composition	Actual rather than nominal GO content; elemental analysis or TGA mass balance
Structure	FTIR plus XPS/Raman; XRD; representative and statistical microscopy
Physical properties	Density, porosity, swelling, water uptake, mechanical data with full curves and replicates
Application data	Appropriate controls, kinetic curves, error bars, real-sample validation and stability
Safety	Extractables/leachables, GO release, cytotoxicity/hemolysis or ecotoxicity as appropriate
Reproducibility	At least three independent batches and disclosure of raw data/analysis scripts

15. CONCLUSIONS

Chitosan–graphene oxide (CS–GO) nanocomposites constitute a versatile class of interface-controlled materials whose performance is governed by chitosan molecular weight and degree of deacetylation, GO oxidation state and size, filler loading, dispersion, cross-linking, and processing history. Strong interfacial interactions between chitosan and GO enable significant improvements in mechanical strength, adsorption, barrier behavior, biological performance, and multifunctionality. The most mature evidence currently supports environmental remediation, membrane treatment, antimicrobial systems, wound dressings, and drug-delivery applications, while emerging studies demonstrate promising roles in microplastic capture, desalination, biosensing, proton-exchange membranes, flexible supercapacitors, anticorrosion coatings, and hydrogen-generation catalysis. Overall, CS–GO should be viewed not as a single fixed material but as a tunable platform whose properties can be engineered for specific applications. Its practical value will ultimately depend on achieving reproducible performance, application-relevant safety, and scalable processing while preserving the sustainability advantages associated with chitosan-based materials.

AUTHOR CONTRIBUTIONS

Conceptualization, literature synthesis, writing original draft, and writing review and editing: to be completed by V Murali Krishna Madasu and other authors.

DATA AVAILABILITY

No new experimental data were generated. The review is based on the literature

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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