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Glycopolymer-engineered materials and surfaces: Immobilized strategies and biomedical applications

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ABSTRACT

Glycopolymers with a brush architecture that are immobilized on material surfaces can mimic the natural glycoconjugates found on cell surfaces, with potential biomedical applications including antimicrobial, anticoagulation, anti-nonspecific adhesion, cellular communication and protein purification. To facilitate the clinical translation and applications of glyco-engineered materials, it is essential to achieve a comprehensive understanding of synthetic strategies and surface-immobilization techniques from a holistic perspective. This review highlights recent advances in the covalent immobilization of glycopolymer chains onto materials through methods like surface-initiated polymerization and interfacial coupling reactions. It provides a detailed summary of the synthetic routes for reactive glycopolymers and interfaces, as well as the technologies used for immobilization on various surfaces, including plastics, metals, silica materials, carbon materials, and living cells. The challenges and opportunities for the future development of glycopolymer-engineered materials and interfaces are also discussed. We believe that this review can serve as a valuable resource for researchers interested in the interdisciplinary field of glycoscience and materials.

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1. Introduction

Carbohydrates are one of four major classes of biomacromolecules, along with lipids, nucleic acids, and proteins. They play crucial roles in numerous physiological and pathological processes, including inflammation, cell differentiation, fertilization, infection, tumor progression, and metastasis [1]. Most glycans are located on the outermost surfaces of cells, linked *via* covalent bonds [2]. This suggests that surface immobilization is a critical step for enabling the functionality of sugar chains. Therefore, decorating native or synthesized glycans on material surfaces can mimic specific interactions with biological systems, making glycosylated materials and interfaces highly valuable for various biomedical applications. Considering that most saccharide ligands bind to their protein receptors very weakly, with binding constants often below 10^6 L/mol, structurally well-defined glycopolymers have been developed to provide polyvalent carbohydrate ligands [3]. This approach enhances the binding constant through the "glycocluster effect" [4]. Glycopolymer synthesis and biomedical applications have been extensively reviewed in recent decades [5]. However, there are currently no reviews focused specifically on glycosylated materials and interfaces. Glycan-decorated surfaces retain the bioactivity of carbohydrates, allowing them to bind lectins or microorganisms in a highly specific manner. Therefore, the straightforward fabrication of glycopolymer-coated surfaces has garnered increasing attention for their diverse bioresponsive behaviors [6].

Controlling the morphology and chemical composition of interfaces is a significant challenge in surface chemistry by customizing the types of sugars, the degree of polymerization, and the grafting density of the polymer brushes [7]. The general approach to surface chemistry involves the growth of polymer brushes from a surface (referred to as "grafted-from") and the covalent attachment of glycans (known as "grafted-to") [8]. Typically, a specially designed linker with reactive terminals is applied to the target substrates. This allows for surface modification through covalent conjugation achieved *via* reactions such as esterification, amidation, or click chemistry with reactive glycopolymers. The surface-initiated living polymerization using glycomonomers can also be employed. Additionally, host-guest interactions are utilized in the fabrication of glycosylated materials, which can provide a stimuli-responsive connection [9].

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Table 1
Summary of glycopolymer-engineered surfaces with different immobilization methods and biomedical applications.

Substrate type	Specific material	Immobilization strategy	Grafting density	Biomedical application	Ref.
Plastics	PS	Surface-initiated ATRP or RAFT, surface amidation	~0.2 molecules/nm^2	Lectin recognition, toxin (BPA) separation	[14–16]
	MPPM	UV-grafting and click chemistry, surface-initiated photopolymerization	~0.20 mmol/cm^2	Lectin recognition, RBC capture, anti-fouling	[17–19]
	Chitosan and agarose	Reductive *N*-alkylation, biotin-streptavidin bioconjugation	~200 nmol/mL	Influenza virus capture and purification	[20,21]
Metals	Gold NPs	Au-S coupling with thiol-terminated glycopolymers	~0.24 molecules/nm^2	Antibacterial photothermal therapy, SARS-CoV-2 biosensing, anti-cancer therapy, stem cell differentiation	[22–26]
	Iron oxide NPs	Silane coupling and Michael addition, Fe-O-P coordination, dopamine adhesion, host-guest interaction	~28 wt%	MRI contrast, magnetic separation, intranuclear imaging, lectin separation	[27–31]
	MOFs	Coordination modulation strategy with carboxylated glycopolymer, glutaraldehyde chemistry using NH_2-functionalized MOFs	~7.12 wt%	Targeted drug delivery, anti-cancer, bacterial detection, glycopeptide enrichment, lectin recognition	[32–35]
Silica materials	Planar silica	Silane coupling and surface-initiated ATRP or RAFT, NHS/PFP ester conjugation, dopamine adhesion, isourea bond formation using the *O*-cyanate chain-end functionalized glycopolymer	~0.12 molecules/nm^2	Hemocompatibility, cell-specific binding, antifogging/antimicrobial coatings, glycan microarray biosensing	[36–41]
	Silica NPs		~0.83 molecules/nm^2	Cell-specific binding, bacterial theranostics, anti-Ebola virus	[42–45]
Carbon materials	CNTs and graphene	Oxidation and surface-initiated ATRP, dopamine adhesion and surface-initiated ATRP, π-π stacking (pyrene anchors)	~8 wt%	Improved dispersibility, targeted lung accumulation, biosensing (lectin interaction), anti-cancer	[46–49]
	Nanodiamonds	Self-assembly and surface photopolymerization, amination and oxime ligation	~0.24 molecules/nm^2	Lectin recognition patterns, targeted drug delivery (*via* GLUT5)	[50,51]
Living cells	HeLa cells and DCs	Non-covalent insertion (cholesterol/lipid anchors), HTP fusion and covalent binding, metabolic labeling and *in situ* CRP	~0.7×10^{-4} molecules/nm^2	Enhanced cell survival, immune cell targeting/activation, disruption of cancer cell migration, improved immunotherapy	[52–59]

The biomedical applications of glycan-coated materials present an exciting opportunity for advanced diagnosis and targeted therapy [10]. When glycans are attached to the surfaces of these materials, the resulting synergistic system undergoes a transformation in its biological features. These "sweet" coatings enhance interfacial hydrophilicity, biocompatibility, protein selectivity, and tissue targeting [11]. For example, heparin coatings are specifically utilized on blood-contact materials to reduce the need for anticoagulants [12]. The tunable affinity of various carbohydrate moieties and brush structures enables a combination of the intrinsic properties of materials with glycobiology [13]. Consequently, surface glyco-engineering illustrates the progress in this field, highlighting the future of glyco-materials and their potential to improve human health.

This review provides a comprehensive overview of glycopolymer-engineered materials and surfaces. It covers a variety of materials, including glycopolymer-coated plastics, metals, silica materials, carbon materials, and living cells. The advanced covalently immobilized technology on different surfaces will be categorized and summarized (Table 1 [14–59]). A discussion about recent trends and developments in innovative synthetic methods and immobilized strategies to create glycan-engineered surfaces is highlighted.

2. Glycopolymer-engineered plastics

Polymer materials are utilized in various biomedical applications, including tissue regeneration, wound dressings, medical adhesives, and surgical consumables [60]. Surface coatings are commonly applied to biopolymers to improve their biocompatibility, durability, functionality, and corrosion resistance in biomedical applications. These coatings can alter the surface properties of polymer materials, making them better suited for their intended uses and enhancing their interactions with biological systems. In this section, we provide an overview of recent methods for immobilizing glycans onto polymer materials, such as microspheres, membranes, and commonly used plastics.

2.1. Glyco-engineered polystyrene (PS) materials

A highly crosslinked and monodispersed PS microsphere serves as an attractive stationary phase for solid-phase extraction and chromatography isolation. Poly(divinylbenzene) (PDVB)-based beads are extensively studied because of the residual double bond on the microsphere's surface, which can be modified through various grafting techniques [61]. Granville *et al.* developed a glycopolymer-modified PDVB bead using reversible addition-fragmentation chain transfer (RAFT) polymerization, incorporating mannosyl and galactosyl monomers (Fig. S1A in Supporting information) [14]. The resulting sugar-coated microspheres exhibited strong recognition properties towards lectins. In another study, Kumar *et al.* utilized commercially available chloromethylated PS resins (Merrifield resin) to prepare a glycopolymer-decorated microsphere, which was used as a solid support for the capture and release of concanavalin A and *Escherichia coli* (*E. coli*) (Fig. S1B in Supporting information) [15]. They synthesized glycopolymers with carboxylic pendants and coupled them with amino-functionalized substrates, resulting in carbohydrate coatings. This glycosylated resin can be regenerated through a reusable column by cell lysis and washing with a mannose solution.

In addition, high internal-phase emulsions (HIPE) copolymerization with styrene (St), divinylbenzene (DVB), and other monomers can produce highly porous foams with functional surfaces [62]. The type of monomers used in the HIPE copolymerization allows for the introduction of reactive sites on the foam surfaces. The poly(St-DVB) foams, which feature fine microstructures and high surface

areas, have garnered significant attention for their ability to selectively adsorb and separate various substances. Yuan and colleagues developed a method to create macroporous polyHIPE foam grafted with surface β-cyclodextrin (β-CD) using surface-initiated atom transfer radical polymerization (ATRP) (Fig. S2A in Supporting information) [16]. The resulting materials demonstrated strong affinity and effective separation of toxic bisphenol A, a common water pollutant. Similarly, Xie *et al*. synthesized a polyHIPE decorated with glycopolymers to rapidly remove boron from wastewater at low concentrations (Fig. S2B in Supporting information) [63].

2.2. Glyco-engineered poly(glycidyl methacrylate) (pGMA)

The pGMA and its copolymers are highly versatile polymer materials featuring reactive oxirane groups that allow for post-polymerization modifications [64]. By treating pGMA-based particles with specially designed nucleophilic agents, it is possible to create new engineered surfaces. In a study conducted by Kaupp, porous pGMA microspheres were prepared using suspension polymerization. Additionally, a glycopolymer containing a thiocarbonyl moiety, which acts as a dienophile, was successfully grafted onto the surface of the microspheres through a pericyclic reaction (Fig. S3 in Supporting information) [65].

2.3. Glyco-engineered microporous poly(propylene) membrane (MPPM)

The MPPM, a highly efficient nanofiltration membrane, has gained popularity across multiple fields due to its remarkable separation capabilities and low energy usage [66]. However, one limitation is its pristine surface, which lacks functional groups necessary for effective glycosylation modifications. Fortunately, UV-induced graft polymerization offers a simple and versatile solution to enhance the surface characteristics of plastics [17]. By utilizing UV irradiation, chemists can generate surface radicals that kickstart free-radical polymerization, allowing for the covalent bonding of vinyl monomers to these reactive sites. To develop a bioselective separation membrane, Xu *et al*. introduced an innovative strategy for achieving high-density glycosylation on MPPMs through surface UV irradiation and click chemistry (Fig. S4 in Supporting information) [18]. The process began with the covalent attachment of carboxyl groups to the membrane surfaces *via* UV-induced grafting of acrylic acid (AA). Subsequently, the AA-grafted surfaces were reacted with propargylamine, yielding alkyne-modified substrates. The final step involved click reactions with glycosyl azides, resulting in glycopolymer coatings on the membranes. The study's findings highlighted that the recognition of lectins on glycosylated MPPMs reveals a significant glycocluster effect when the glycosyl density on the surface exceeds 0.20 mmol/cm^2, showcasing the potential for enhanced bioselectivity in practical applications. Moreover, surface-initiated photopolymerization was strategically utilized to develop a glycopolymer-patterned surface on elastomer materials, specifically designed to capture red blood cells (RBCs) effectively [19]. These glycosylated layers not only retain their hydrophilic nature, which is crucial for preventing non-specific adsorption of plasma proteins, but also exhibit an exceptional ability to capture RBCs from blood, making them a promising solution for biomedical applications.

2.4. Glyco-engineered natural polymer materials

In addition to the synthetic plastics mentioned earlier, glycan modification has also been applied to certain natural polymer materials that possess reactive sites, such as amino groups or hydroxylic groups on their surfaces. Chitosan, for instance, has been widely used in biomedical applications due to its excellent biocompatibility, biodegradability, and antimicrobial properties [67]. Li *et al*. prepared a chitosan fiber functionalized with sialic acid for capturing the influenza virus (capture rate >90 %) [20]. The lactose with an aldehyde linker reacted with amines on chitosan to form an imine structure, which could then be reduced to create a stable C–N bond using sodium cyanoborohydride. Subsequently, an enzymatic sialylation process was conducted to introduce α−2,3-sialylactose units onto the chitosan backbone. This surface-sialylated chitosan fiber served as an effective platform for filtering and providing protection against influenza virus infections (Fig. S5A in Supporting information). In a recent advancement, Ye *et al*. introduced a surface-glycosylated agarose bead featuring custom-synthesized glyco-clusters, enabling selective separation of the influenza virus using streptavidin-derivatized sepharose resin (Fig. S5B in Supporting information) [21]. More than 50 % of intact viral particles were recovered using this glycopolymer-modified sepharose chromatography. This innovative glycopolymer was end-functionalized with a biotin group for effective conjugation to streptavidin. As a result, a reusable virus-affinity chromatography assay was established utilizing sialylglycopolymer-coated streptavidin sepharose, paving the way for continuous and efficient virus purification. More recently, Ogata *et al*. presented the synthesis of multivalent glycoside-immobilized carboxymethyl cellulose nanohydrogel particles (glyco-CMCGPs) as high-performance adsorbents for lectins [68]. They discovered that increased multivalency enhances avidity through the glycocluster effect; however, beyond a certain density, steric hindrance or reduced accessibility may limit further increases in avidity per sugar unit.

Overall, the synthetic plastics like PS, pGMA, and pMPPM, offer versatility, ease of fabrication into various forms (such as microspheres, foams, membranes), and often possess inherent reactive sites for glycan modification. Natural polymers like chitosan, agarose, and cellulose provide excellent biocompatibility and biodegradability. Surface-initiated polymerization and surface-mediated conjugation reactions are powerful techniques for creating advanced glyco-engineered surfaces on plastic surfaces. Utilizing difunctional monomers like DVB and DMA enables the direct placement of reactive sites on material surfaces, enhancing their functionality. Moreover, surface UV irradiation is a highly effective method for producing reactive radical species on plastic substrates, initiating surface polymerization. These innovative glycopolymer brushes open up exciting opportunities for biomedical applications, including the lectin recognition, toxin separation, virus capture and purification, as well as RBCs capture. Embracing these methods allows for the development of cutting-edge solutions in medical and biotechnological fields.

3. Glycopolymer-engineered metal materials

Metal nanoparticles (NPs), including gold (Au), silver (Ag), and iron oxide, are at the forefront of innovative biomedical applications, such as cancer treatment, drug delivery, antibacterial strategies, and diagnostic assays [69]. Coating these metal NPs with glycans can improve their biocompatibility and enable them to selectively recognize and target specific cells for precise diagnosis and therapy. This section will delve into the realm of advanced glycosylated metals and the cutting-edge synthetic strategies employed to immobilize glycans on their surfaces, showcasing their potential to revolutionize biomedical practices.

3.1. Glyco-engineered gold materials

Gold NPs represent a groundbreaking and highly functional class of materials, offering unprecedented biomedical applications

due to their unique optical, chemical, and physical properties, particularly the near-infrared (NIR) photothermal effect [70]. Modified glycan coatings enhance their antitumor and antibacterial efficacy, as the attached sugar brushes effectively target and capture pathogens [71]. A widely adopted method for modifying gold surfaces involves the gold-sulfur coupling reaction, enabling the incorporation of biomolecules, polymers, or ligands. This process typically employs RAFT polymerization with glycosyl monomers, resulting in end-group functionalized glycopolymers. These glycopolymers can subsequently be transformed into thiol-terminated structures through reduction with sodium borohydride. As shown in Fig. S6 (Supporting information), they can then be immobilized on gold surfaces in a single-step process (Fig. S6A). For example, Zhang *et al*. synthesized glycomimetic-decorated gold nanorods to treat aminoglycoside-resistant *P. aeruginosa* infections (Fig. S6B) [22]. The significant inhibition of biofilm formation and bacterial killing can be attributed to the synergistic effects of carbohydrate-mediated pathogen enrichment and the localized hyperthermia generated from NIR irradiation.

Furthermore, glycopolymer-modified gold NPs or substrates offer significant potential for biosensing applications. Gibson *et al*. synthesized gold NPs coated with sialyllactose-functionalized polymers for the rapid detection of severe acute respiratory syndrome coronavirus 2 (SARS–CoV–2) (Fig. S6C) [23]. This method exploited the interaction between the viral spike protein and sialic acids, allowing for detection in under 30 min using a pseudotyped lentivirus model. Such advancements highlighted the remarkable potential of glycan-based nanogold as an efficient detection platform. Additionally, Saito *et al*. developed a biosensor platform that merged gold-capped nanopillars with length-controlled glycopolymers for quick and sensitive cytokine detection [24]. This strategy took advantage of localized surface plasmon resonance (LSPR) for label-free detection and ensured specificity through precise glycan-protein interactions.

Moreover, several natural sulfated polysaccharides known for their anticancer properties have been effectively incorporated into gold modifications for combination therapies. Research by Oommen *et al*. demonstrated the successful synthesis of fucoidan-mimetic glycopolymer-coated gold NPs, revealing their significant anticancer potential [25]. This innovative biomimetic glycopolymer-NP hybrid showed remarkable selective cytotoxicity toward human colon cancer cell lines while remaining non-toxic to mouse fibroblast cells (Fig. S6D). Additionally, ribonuclease (RNase), recognized for its ability to inhibit tumor growth and metastasis, was conjugated with glyco-gold NPs, further enhancing the targeted photothermal killing of cancer cells [26]. Recent studies have also highlighted glycosylated gold nanocomposites as promising nanomedicines for enhancing stem cell differentiation into neural cells, which could be beneficial in treating neurodegenerative diseases [72]. By leveraging the combined power of gold NPs and glycan coatings, these nanocomposites can activate crucial signaling pathways, including the glycosaminoglycan (GAG)-related pathway (extracellular signal-regulated kinases 1/2, ERK1/2) and the retinoic acid (RA)-related pathway. This innovative approach holds great potential for breakthroughs in regenerative medicine.

3.2. Glyco-engineered iron oxide materials

Iron oxide NPs are an incredibly effective scaffold for fabricating glyco-nanomaterials by grafting glycopolymers onto their surfaces. Their remarkable magnetic properties enhance their utility in a variety of biomedical applications, including magnetic resonance imaging (MRI), magnetic separation, targeted drug delivery, and hyperthermia treatment for cancer [73]. The incorporation of glycopolymer shells on iron oxide materials significantly reduces cytotoxicity and enhances biocompatibility, which is crucial for effective tissue targeting and biological recognition of the individual magnetic cores [74]. Müller *et al*. developed glycopolymer hybrid NPs that possess both magnetic and fluorescent properties, making them suitable for intranuclear optical imaging [27]. The iron oxide particles were treated with trialkoxy silane reagents through a ligand exchange process, resulting in a vinyl-functionalized surface [75]. Following this, as shown in Fig. S7 (Supporting information), a glycopolymer with a fluorescent pendant was conjugated using a Michael addition reaction (Fig. S7A). This modification of the glycopolymer shell improved the solubility of the NPs in aqueous environments and enabled their uptake by lung cancer cells through galactose-hepatocyte recognition mechanisms.

Additionally, the reaction between iron oxide and the phosphoric acid anchoring group created crucial bidentate or tridentate Fe-O-P coordination bonds [28]. These bonds can serve as reactive sites that facilitate the conjugation of targeting ligands, enhancing the functionality of the NPs. For instance, Davis *et al*. successfully synthesized phosphoric acid-terminated glycopolymers specifically designed for modifying iron oxide NPs (Fig. S7B) [29]. The resulting glycosylated magnetic particles are not only quantifiable through MRI but also exhibit a remarkable increase in cellular uptake, showcasing their potential for advanced biomedical applications [30]. Another approach involves leveraging dopamine adhesion alongside host-guest chemistry on the NP surface. Sanyal *et al*. pioneered the fabrication of glycopolymer-coated magnetic NPs using supramolecular host-guest techniques aimed at selective lectin separation (Fig. S7C) [31]. By modifying the surfaces with adamantane-terminated poly(ethylene glycol) brushes, they enabled the non-covalent attachment of β-CD derivatives conjugated with star-shaped glycopolymers. This process not only streamlines protein purification through selective capture but also facilitates scalable recovery, making it a promising solution for the future of biochemical applications.

Apart from the methods mentioned above, treating biotin-tagged glycopolymers with streptavidin-coated magnetic particles may offer an effective solution for the rapid capture and removal of toxins from water [76]. The presence of additional carboxylic groups allows for electrostatic interactions with the iron oxide surface, providing another means of attachment [77]. These glycopolymer-coated superparamagnetic NPs demonstrate long-term stability and enhanced water solubility, making them suitable for a wide range of biomedical applications.

3.3. Glyco-engineered metal-organic framework (MOF)

MOFs represent a new generation of organic-inorganic hybrid porous materials that have garnered significant interest in the biomedical field. Their remarkable internal porosity, customizable structures, and ease of surface modification present tremendous opportunities for advancing healthcare solutions [78]. However, the potential of MOFs is somewhat constrained by their limited stability in aqueous environments, which poses a challenge for widespread application and commercialization [79]. To overcome this barrier, integrating biomacromolecules onto the surface of MOFs has proven to be a highly effective method for enhancing their stability and imparting diverse functionalities [80]. Notably, Forgan and his team employed a coordination modulation strategy to develop a glycopolymer-decorated MOF(Zr), creating a targeted dual delivery system with cancer-fighting capabilities [32]. The specially designed diblock glycopolymer, rich in carboxylate groups, effectively coordinates with the Zr6 units on the MOF (Fig. S8 in Supporting information), enhancing its performance. The glycan coatings improved the uptake of MOF NPs in cancer cells and provided significantly selective drug delivery, resulting in high cytotoxicity against HepG2 human hepatocellular carcinoma cells.

Luminescent LMOFs have significantly advanced the detection capabilities for a wide array of toxic, hazardous, and biologically important substances [81]. Notably, Bhatt *et al*. developed an innovative glyco-conjugated MOF biosensor that excels in the fluorescent detection of Pseudomonas aeruginosa and *E. coli* [33]. By modifying an NH_2-functionalized Fe-MOF with sugars through glutaraldehyde chemistry, they created probes that leverage the unique tunable properties of MOFs alongside carbohydrate specificity, setting a new standard in bacterial sensing. Moreover, this glyco-engineered MOF stands out as an effective tool for protein enrichment. Liu *et al*. contributed to this field by designing a maltose-functionalized Cr-MOF *via* the targeted modification of amino groups on its surfaces [34]. This advanced nanomaterial successfully detected and isolated *N*-linked glycopeptides from human immunoglobulin G digests, highlighting its potential for complex biomolecular applications. Furthermore, the addition of a small amount of concanavalin A induced an aggregation phenomenon in the colloidal Glyco-MOF solution, underlining its remarkable efficiency in lectin-recognition analysis [35].

Metal NPs provide unique optical, magnetic, and photothermal properties. MOFs offer extremely high surface area and tunable porosity. However, their practical use in living organisms is often hindered by the agglomeration that occurs in biological fluids, which is a result of their high surface energies and propensity to adsorb proteins. By utilizing glycan engineering on the metal surface, it is possible to stabilize these NPs, enhance their targeting ability within biological environments, and increase their blood circulation half-life, thus broadening their potential biomedical applications. Over the last decade, significant research has focused on synthesizing glycosylated metal surface for a variety of promising biomedical applications, such as antibacterial photothermal therapy, biosensing, targeted drug delivery for cancer therapy, MRI, and magnetic separation.

4. Glycopolymer-engineered silica materials

Silica-based materials, especially mesoporous silica NPs and planar silica wafers, have emerged as versatile platforms in various biomedical research fields due to their remarkable bioactivity, excellent biocompatibility, easy surface functionalization, and controllable synthesis [82]. The high surface area and porous structure of these materials make them suitable for applications in drug delivery and diagnostic imaging [83]. However, despite their potential, challenges such as long-term biocompatibility still exist. Improving surface chemistry, like through surface glycosylation, has been identified as a significant method to enhance their interfacial properties and facilitate clinical translation. For example, the heparinized silicone surface has been fabricated for attractive anticoagulation [84]. The resulting heparin-modified silicone material demonstrates significantly enhanced anticoagulant capacity, paving the way for its application as an *in vivo* implantable catheter material (Table S1 in Supporting information).

The modification of silica surfaces begins with the crucial step of introducing functional groups through silane coupling agents, setting the stage for effective surface functionalization. As shown in Fig. S9 (Supporting information), Kizhakkedathu *et al*. made significant strides by synthesizing glycopolymer brushes on silica substrates using surface-initiated ATRP (Fig. S9A) [36]. This innovative approach resulted in a biomimetic interface that demonstrates excellent hemocompatibility. Their findings underscore the vital importance of carbohydrate structure in crafting blood-contacting devices, such as stents and catheters, that significantly reduce thrombogenicity. In a similar approach, Chen *et al*. developed cell-specific glycosurfaces on silicon slices using surface-initiated copper-mediated reversible deactivation radical polymerization, in the presence of live EpCAM-positive and EpCAM-negative HeLa cells [37]. This work represents an advancement in the design of cell-specific materials, providing a simple, scalable, and reusable platform. In another grafting-from example, Jana *et al*. reported the synthesis of glycopolymer-coated silica NPs using RAFT polymerization (Fig. S9B) [38]. The dithiobenzoate-based RAFT agents were covalently attached to the surface of silica particles through an amide bond, facilitating the growth of a mannose-based glycopolymer chain. Additionally, the post-polymerization modification strategy contributed to the synthesis of the glycosylated layer. Caykara *et al*. prepared poly(pentafluorophenyl acrylate) (pPFP) brushes on a silicon substrate using interface-mediated RAFT polymerization, followed by the attachment of glucosamine through PFP ester conjugation (Fig. S9C) [39]. This amine-reactive coupling chemistry, such as *N*-hydroxysuccinimide (NHS) ester or PFP ester conjugation, enabled various surface coatings by forming covalent bonds. In another example, a reactive glycopolymer chain was synthesized through copolymerization, utilizing a polymerizable silane coupling reagent that contains a vinyl group, along with protected glycosyl monomers [85]. This glycopolymer can directly modify a silica surface when applied. After the deprotection process, the resulting glyco-film is used for selective bioseparation and in photonic crystal biosensors [86]. It should be noted that a longer or more flexible linker may allow better accessibility to lectin binding sites, but may also lead to non-specific adsorption or reduced multivalency due to entropy loss upon binding.

Recently, antifogging coatings on optical devices have gained significant attention for maintaining a clear surgical field during laparoscopic procedures in high-humidity environments [87]. One effective solution is the construction of superhydrophilic layers, such as glycopolymer coatings. Chen *et al*. developed a sunlight-initiated polymerization technology to synthesize dopamine-sugar diblock copolymers with surface anchoring capabilities (Fig. S9D) [40]. In their process, glass slides or silicon wafers were immersed in a Tris–HCl buffer solution containing glycopolymers. This immersion led to the formation of glycosylated surfaces through catechol groups, resulting in excellent antifogging properties and superior antimicrobial activity against both Gram-negative *E. coli* and Gram-positive Staphylococcus aureus [41]. Additionally, this immobilization technology was utilized to create glycopolymer-modified surface-enhanced Raman scattering (SERS) substrate to investigate specific interaction between carbohydrates and proteins [88].

On the other hand, silica-based glycan microarrays are emerging as innovative tools for the rapid detection of carbohydrate-binding biomarkers that may indicate various disease states [89]. A noteworthy advancement in this area is the novel glycopolymer microarray architecture which achieves remarkable subfemtomolar avidity for glycan-binding proteins (GBPs), particularly concanavalin A (ConA), through the use of hypersurface photolithography technology [90]. This innovation effectively tackles long-standing challenges associated with weak glycan-protein interactions and complex synthesis processes, establishing a new benchmark in glycan microarray technology. In addition, Dong and his colleagues have made impressive strides in creating a multifunctional platform designed to address both diagnostic and therapeutic challenges related to bacterial infections [42]. By integrating europium, glycopolymer-modified silica NPs, and black phosphorus, they have created a targeted approach for bacterial imaging and ablation. The glycosylated surface modification allows for precise targeting of *E. coli* K12, significantly minimizing off-target effects. Meanwhile, black phosphorus effectively eradicates bacteria through oxidative stress and physical penetration. This cutting-edge strategy not only enhances the capabilities in precision medicine but also lays the groundwork for the future development of theranostic glyco-nanomaterials.

Beyond traditional immobilization techniques, innovative reactive polymers have been developed for surface glycoengineering

on glass slides and other silica materials. For instance, Sun *et al*. synthesized an *O*-cyanate chain-end functionalized glycopolymer that effectively adheres to amine-functionalized glass slides through isourea bond formation under alkaline conditions [43]. Furthermore, by immobilizing *O*-cyanate chain-end functionalized sialyllactose-containing glycopolymers onto amine-modified SPR chips, they successfully created a SPR-based glyco-biosensor [44]. This biosensor represents a significant advancement in high-throughput methods for virus diagnosis and the screening of potential antiviral drug candidates. Additionally, the application of glyco-dendrimers on silica NPs has been shown to enhance multivalent carbohydrate presentation in DC-SIGN (dendritic cell-specific intercellular adhesion molecule-3-grabbing non-integrin)-mediated viral infection models [45]. Impressively, these mannosylated NPs exhibited remarkable inhibitory activity against the Ebola virus, highlighting a promising avenue for developing targeted antiviral nanomedicines that leverage the DC-SIGN pathway.

Overall, silica materials boast excellent biocompatibility, ease of functionalization *via* silane chemistry, optical transparency, and a porous structure suitable for drug loading. Glycopolymer-engineered silica materials represent a versatile advancement in biomedicine, effectively bridging the gap between inorganic materials and clinical needs. Surface glycosylation enhances biocompatibility and reduces thrombogenicity, which is crucial for implants such as stents. Silane coupling followed by surface-initiated ATRP/RAFT, NHS/PFP ester conjugation, dopamine adhesion, and isourea bond formation is the widely-used immobilization technique. Heparin-modified silicone surfaces drastically reduce fibrinogen adsorption and thrombin generation, making them ideal for blood-contacting devices like catheters and stents. Glycopolymer coatings on glass form superhydrophilic layers that prevent fogging on surgical lenses and exhibit antimicrobial activity against *E. coli* and *S. aureus*. SPR-based biosensors using immobilized glycopolymers could be used for virus diagnosis and drug screening.

5. Glycopolymer-engineered carbon materials

Carbon materials, especially advanced carbon nanostructured forms like graphene, nanotubes, and quantum dots, present exciting possibilities for biomedical applications. Their remarkable physicochemical properties, ranging from superior electrical and optical capabilities to impressive catalytic activities, make them ideal candidates for innovative medical solutions [91]. Despite their potential, carbon-based therapies have struggled to achieve clinical acceptance due to challenges like biocompatibility, nanotoxicity, target specificity, and various biointerfacial effects [92]. To address these issues, effective surface modifications are applied to functionalize or modify the carbon nanostructures utilized in biological applications.

Enhancing the solubility, safety, and biodegradability of carbon materials can be effectively achieved through surface glycosylation with glycopolymers. Before surface glycosylation, carbon nanotubes (CNTs) are typically oxidized to create carboxylic sites, which are essential for the subsequent amidation coupling. Using this strategy, as shown in Fig. S10 (Supporting information), CNTs can be functionalized with a surface-initiated ATRP initiator, specifically 2–bromo-2-methylpropionyl bromide, enabling surface-initiated polymerization (Fig. S10A) [46]. Sugar-carrying acrylamide monomers are then polymerized from the surface of the CNTs, resulting in glycan coatings. To streamline the coating process, Wei *et al*. introduced an efficient method for modifying CNTs with glycosylated polymers. This approach utilizes mussel-inspired chemistry *via* dopamine self-polymerization to create polydopamine coatings on CNTs. Following this, ATRP is applied to graft polymers onto the CNTs (Fig. S10B) [47]. The modified CNTs show significantly improved dispersibility in aqueous solutions, which is essential for their use in biomedical applications. Mussel-inspired chemistry offers several advantages over traditional surface modification techniques, including milder reaction conditions and the ability to functionalize a diverse range of materials. Additionally, researchers investigated the role of glycans in influencing biodistribution *in vivo* by using glyco-functionalized single-walled CNTs (SWCNTs) [48]. *N*-Acetyl-D-glucosamine (GlcNAc) and lactose were modified on the surface of SWCNTs through a linker unit. The glycans were found to improve the dispersibility of the nanotubes but did not significant alter their biodistribution. Moreover, the GlcNAc-modified SWCNTs accumulated specifically in the lungs, with no leakage of the radionuclide to high-affinity organs like the thyroid or stomach [49]. The authors suggest that the glycosylated surface might interact with lung-specific proteins. However, the GlcNAc- specific endothelial receptors remain undiscovered.

Recently, Claridge *et al*. unveiled a method for crafting glycopolymer nanopatterns on material surfaces. By designing and synthesizing diacetylene amphiphiles with carbohydrate headgroups, they successfully generated nanometer-resolution patterns on highly oriented pyrolytic graphite (HOPG), followed by photopolymerization into a robust polyacrylamide (PAAm) network [50]. These advanced glycopolymer patterns facilitated selective and multivalent interactions with lectins, showcasing their potential in various applications. However, it is important to further explore the long-term stability of these patterns in physiological conditions to fully understand their utility. Except for the traditional carbon materials, Xiao *et al*. highlighted the promising use of glycopolymer-coated nanodiamonds for targeted drug delivery in breast cancer therapy (Fig. S10C) [51]. Through surface amination using a specific silane coupling agent and subsequent oxime-aldehyde ligation, they achieved fructose coatings with a high density of glycopolymer grafting. These fructose moieties significantly enhanced cellular uptake *via* GLUT5 transporters, which are known to be overexpressed in breast cancer cells, illustrating a targeted approach that could revolutionize treatment strategies.

Additionally, supramolecular coupling emerges as a highly effective strategy for the glycosylation of carbon surfaces. Bertozzi *et al*. took a significant step forward by functionalizing SWCNTs with glycodendrimers. These glycodendrimers feature peripheral carbohydrate units attached to a pyrene tail, which interacts with SWNTs through strong π-π interactions (Fig. S10D) [93]. This innovative glycodendrimer coating markedly reduces cytotoxicity, enabling cells to thrive and proliferate in their presence. In a similar strategy, Chen *et al*. succeeded in creating a biocompatible interface by anchoring sugar moieties to the nanotubes with either a pyrene or lipid tail [94]. The pyrene-based linker formed a uniform layer and showed better lectin binding compared to the lipid linker. The resulting glycosylated SWCNTs were used to create thin-film network devices capable of detecting exocytosis events triggered by high potassium solutions or calcium ionophores, exhibiting high temporal resolution and sensitivity. Dag and his team conducted an insightful comparison of noncovalent and covalent functionalization strategies to significantly enhance the biocompatibility and targeting efficiency of glycosylated multi-walled CNTs (MWCNTs) [95]. By employing either π-π stacking (noncovalent) or a copper-catalyzed azide-alkyne click reaction (covalent) for attaching glycopolymers to CNTs, they discovered that the noncovalent method yielded a superior loading of glycopolymers. Notably, both noncovalent and covalent coatings enhanced cellular uptake and cytotoxicity in MCF-7 and MDA-MB-231 breast cancer cell lines, indicating their potential as effective drug delivery systems. Additionally, a noncovalent complex of SWCNTs wrapped in glycopolymer layers was synthesized [96]. The intrinsic NIR fluorescence of SWCNTs was used to monitor interactions between carbohydrates and lectins. This demonstrated the

potential of glyco-SWCNTs as versatile optical sensors for detecting carbohydrate-protein interactions with improved specificity and sensitivity.

In summary, this section emphasizes the critical importance of functionalizing carbon nanomaterials with glycopolymers. Carbon nanomaterials (nanotubes, graphene, nanodiamonds) possess exceptional electrical, optical, and mechanical properties, but face challenges in solubility and nanotoxicity. Surface modification with glycopolymers significantly improves biocompatibility, though long-term biosafety requires rigorous evaluation. Techniques such as covalent grafting and noncovalent π-π interactions are essential for creating effective carbohydrate coatings on carbon surfaces. Glycosylation significantly improves the water dispersibility of CNTs. Notably, GlcNAc-modified SWCNTs show specific accumulation in the lungs, suggesting potential for lung-targeted applications. Fructose-coated nanodiamonds are selectively taken up by breast cancer cells *via* overexpressed GLUT5 transporters, enabling targeted therapy. This glycoengineering of the carbon nanomaterials transforms them from promising yet problematic candidates into highly functionalized, biocompatible platforms with significant potential for targeted drug delivery, sensitive biosensing, and other advanced biomedical applications.

6. Glycopolymer-engineered cells

Glycan chains on cell surfaces play a crucial role in various biological processes. However, the complex structures and distribution of glycans create significant challenges for functional studies [97]. To gain a better understanding of glycan functions, it is essential to develop cell models with relatively homogeneous glycan structures. Consequently, modifying the glycan structures on cell surfaces becomes particularly important. Several methods for cell surface glycoengineering have been reported, including passive exogenous insertion, genetic techniques, and metabolic labeling. This section will summarize the main strategies for surface glycoengineering on cells and discuss their biological effects.

The non-covalent insertion of synthetic glycopolymers into live cell membranes marks a significant advancement in cell surface engineering [98]. This method enables precise control over the chemical composition and density of glycopolymers on the cell surface, which is essential for studying cell-surface phenomena. Bertozzi *et al.* investigated synthetic glycopolymers that mimic cell-surface mucins, focusing on their ability to enhance cell survival *in vivo* [52]. They prepared a variety of glycopolymers with different lipid anchors to examine their persistence on cell membranes. The study found that glycopolymers anchored with cholesterylamine (CholA) were internalized into vesicles but continuously recycled back to the cell surface, facilitating efficient glycan coating on the surface (Fig. S11A in Supporting information). Furthermore, in a zebrafish model of metastasis, MCF-10A cells coated with cholesterol-anchored glycopolymers exhibited significantly higher survival rates compared to the uncoated cells. Following a similar strategy, Kramer *et al.* synthesized glycopeptides with a hydrophobic CholA terminal to mimic mucin structures [53]. These glycopeptides were created through the polymerization of amino acid *N*-carboxyanhydrides (NCAs). The results of cell modification indicated that the CholA-terminated glycopeptide could be effectively incorporated into the cell membrane and maintained for several days. Additionally, block polymers containing sugar and cholesterol units were used for cell surface modification. Chen and colleagues synthesized a glycopolymer with varying cholesterol content [54]. Cholesterol facilitated stable insertion into the membrane, while the adjustable cholesterol content regulated polymer internalization. However, higher cholesterol levels were found to reduce endocytosis, thereby extending the functional display of the polymers.

Except for the noncovalent approach, several other promising methods have been developed. Chen *et al.* utilized a combination of the HaloTag protein (HTP) fusion technique and RAFT polymerization to create a stable attachment of glycopolymers (containing GlcNAc and ManNAc) to the surface of HeLa cells (Fig. S11B in Supporting information) [55]. These glycopolymers, featuring a chloroalkane terminal, could be rapidly and specifically linked to HTP. The modified glycans then bind to lectins on macrophages and dendritic cells (DCs), promoting the M1 polarization of macrophages and enhancing the maturation of dendritic cells. Using glycopolymers to target immune cells may improve the specificity and efficacy of cancer treatments. Furthermore, DCs were also modified with synthetic glycopolymers that demonstrated improved interactions with T cells, resulting in enhanced T cell activation and increased tumor cytotoxicity [56]. Notably, it was discovered that glycopolymers interact with programmed cell death protein 1 (PD-1) on T cells, which opens up new possibilities for combining this approach with immune checkpoint blockade therapies. The same research group also synthesized glycopolymers with chloroalkane motifs and attached them to tumor cells using the HTP strategy [57]. The modified cancer cells exhibited reduced directional diffusion and a tendency to rotate around their original position. These findings suggest that glycopolymer-modified cancer cells could disrupt the collective migration of cancer cells, potentially slowing down metastasis.

More recently, Ju *et al.* developed a site-selected, *in situ* controlled radical polymerization (CRP) method that allows for precise control of polymer grafting sites on cell surfaces (Fig. S11C in Supporting information) [58]. This technique combines metabolic labeling techniques with a Fenton-RAFT polymerization process, which is cytocompatible and enables the growth of glycopolymers at specific locations on the cell membrane. This approach could be utilized to engineer immune cells with enhanced resistance to certain types of cell death, potentially leading to significant advancements in cancer immunotherapy and other therapeutic applications. Chemically modified sugars, unlike their natural counterparts, have shown a remarkable capacity to enhance immune responses. Ye *et al.* synthesized fluorine-modified monosaccharides and expressed them on the surface of tumor cells using the technology of metabolic oligosaccharide engineering (MOE), thereby obtaining extracellular vesicles containing non-natural tumor-associated carbohydrate antigens [59]. This cell-derived material with special glycan profiles enhanced the function of immune cells and improved the efficacy of tumor immunotherapy. In addition, the synthetic glycopolymers can also effectively mimic and enhance the bioactivity of complex natural glycans like lipopolysaccharide (LPS) [99]. This provides a versatile platform for designing tunable immune adjuvants where specific control over carbohydrate-receptor interactions is desired.

Overall, the surface-modified glycopolymers used on living cells tackle the challenge of natural glycan heterogeneity. Direct cell surface engineering allows for the creation of homogeneous, tunable glycan displays on living cells to study and modulate biological functions, overcoming natural heterogeneity. This advancement enables more detailed mechanistic studies of sugar-mediated biological processes. Cancer cells coated with cholesterol-anchored glycopolymers show significantly higher survival rates *in vivo* and disrupted migration patterns, potentially slowing metastasis. Glycopolymers attached to immune cells (DCs, macrophages) enhance their activation, maturation, and tumor-targeting capabilities. They can also interact with PD-1 on T cells, suggesting the potential for combination with checkpoint blockade therapy. The combination of carbohydrate chemistry and cell biology highlights the importance of glycans as essential players in cellular communication.

7. Conclusions

This review underscores that glycopolymer engineering is a powerful and versatile strategy to impart bio-recognition, improved biocompatibility, and targeted functionality to a wide range of material classes. The choice of substrate material dictates the available immobilization strategies, and unlocks unique biomedical applications from sensing and separation to targeted therapy and immunotherapy. The strategic presentation of glycopolymers on material surfaces allows us to replicate the glycocalyx typical of cell membranes, thereby driving a variety of critical biological processes. The advancement of interfacial glycosylation technology is not only pivotal for the design of cutting-edge materials and their biomedical uses but also for enriching biological research. These glyco-engineered surfaces, featuring uniform sugar chains, unlock profound insights into the essential functionality of glycans, empowering us to deeply understand the vital biological signals encoded in sugars that reside on cellular surfaces.

CRediT authorship contribution statement

Gefei Li: Writing – review & editing, Writing – original draft. **Juan Mo:** Writing – original draft. **Yi Deng:** Writing – original draft. **Wenhuan Zhong:** Writing – original draft. **Qinhan Chen:** Writing – original draft. **Xin-Shan Ye:** Writing – review & editing, Supervision.

Declaration of competing interest

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

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Supplementary materials

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References

[1] A. Varki, Glycobiology 27 (2017) 3–49.
[2] C. Reily, T.J. Stewart, M.B. Renfrow, J. Novak, Nat. Rev. Nephrol. 15 (2019) 346–366.
[3] J.J. Lundquist, E.J. Toone, Chem. Rev. 102 (2002) 555–578.
[4] J.L. Jiménez Blanco, C. Ortiz Mellet, J.M. García Fernández, Chem. Soc. Rev. 42 (2013) 4518–4531.
[5] J. Wang, J. Zhou, Y. Ding, X. Hu, Y. Chen, Polym. Chem. 14 (2023) 2414–2434.
[6] C. von der Ehe, C. Weber, M. Gottschaldt, U.S. Schubert, Prog. Polym. Sci. 57 (2016) 64–102.
[7] C. Carbonell, D. Valles, A.M. Wong, et al., Nat. Commun. 11 (2020) 1244.
[8] N.C. Reichardt, M. Martín-Lomas, S. Penadés, Chem. Soc. Rev. 42 (2013) 4358–4376.
[9] H. Zhu, L. Chen, B. Sun, et al., Nat. Rev. Chem. 7 (2023) 768–782.
[10] X. Yan, L. Chai, E. Fleury, F. Ganachaud, J. Bernard, Prog. Polym. Sci. 120 (2021) 101429.
[11] K. Arora, P.M. Sherilraj, K.A. Abutwaibe, B. Dhruw, S.L. Mudavath, Int. J. Biol. Macromol. 268 (2024) 131511.
[12] S. Cheng, H. Ji, T. Xu, et al., J. Mater. Chem. B 12 (2024) 10994–11011.
[13] U.I.M. Gerling-Driessen, M. Hoffmann, S. Schmidt, N.L. Snyder, L. Hartmann, Chem. Soc. Rev. 52 (2023) 2617–2642.
[14] A. Pfaff, L. Barner, A.H.E. Müller, A.M. Granville, Eur. Polym. J. 47 (2011) 805–815.
[15] J.K. Ajish, H.M. Abraham, M. Subramanian, K.S.A. Kumar, Macromol. Biosci. 21 (2020) 2000342.
[16] C. Wang, X. Chen, W. Yuan, M. Zhou, New J. Chem. 47 (2023) 11643–11650.
[17] J. Deng, L. Wang, L. Liu, W. Yang, Prog. Polym. Sci. 34 (2009) 156–193.
[18] C. Wang, J. Wu, Z.K. Xu, Macromol. Rapid Commun. 31 (2010) 1078–1082.
[19] C. Zhao, Q. Shi, J. Hou, et al., J. Mater. Chem. B 4 (2016) 4130–4137.
[20] X. Li, P. Wu, G.F. Gao, S. Cheng, Biomacromolecules 12 (2011) 3962–3969.
[21] G. Li, W. Ma, J. Mo, et al., ACS Appl. Mater. Interfaces 13 (2021) 46260–46269.
[22] Y. Zhao, Q. Guo, X. Dai, et al., Adv. Mater. 31 (2018) 1806024.
[23] A.N. Baker, S.-J. Richards, C.S. Guy, et al., ACS Cent. Sci. 6 (2020) 2046–2052.
[24] Y. Terada, A. Obara, H. Takamatsu, et al., ACS Appl. Bio Mater. 4 (2021) 7913–7920.
[25] M. Tengdelius, D. Gurav, P. Konradsson, et al., Chem. Commun. 51 (2015) 8532–8535.
[26] Y. Zhao, R. Jia, Y. Liu, et al., Mater. Today Commun. 28 (2021) 102640.
[27] A. Pfaff, A. Schallon, T.M. Ruhland, et al., Biomacromolecules 12 (2011) 3805–3811.
[28] C. Lu, L.R. Bhatt, H.Y. Jun, S.H. Park, K.Y. Chai, J. Mater. Chem. 22 (2012) 19806–19811.
[29] J.S. Basuki, L. Esser, H.T.T. Duong, et al., Chem. Sci. 5 (2014) 715–726.
[30] J. An, X. Zhang, Q. Guo, et al., Colloids Surf. A 482 (2015) 98–108.
[31] Y. Oz, Y. Abdouni, G. Yilmaz, C.R. Becer, A. Sanyal, Polym. Chem. 10 (2019) 3351–3361.
[32] F. Demir Duman, A. Monaco, R. Foulkes, C.R. Becer, R.S. Forgan, ACS Appl. Nano Mater. 5 (2022) 13862–13873.
[33] D. Bhatt, S. Singh, N. Singhal, N. Bhardwaj, A. Deep, Anal. Bioanal. Chem. 415 (2022) 659–667.
[34] W. Ma, L. Xu, Z. Li, et al., Nanoscale 8 (2016) 10908–10912.
[35] R.E. Giménez, E. Piccinini, O. Azzaroni, M. Rafti, ACS Omega 4 (2019) 842–848.
[36] K. Yu, B.F.L. Lai, J.N. Kizhakkedathu, Adv. Healthc. Mater. 1 (2012) 199–213.
[37] X. Ma, Y. Luo, P. Zhang, et al., Macromol. Rapid Commun. 44 (2023) 2200881.
[38] S.N.R. Kutcherlapati, R. Koyilapu, U.M.R. Boddu, et al., Macromolecules 50 (2017) 7309–7320.
[39] T.T. Kursun, D. Cimen, T. Caykara, J. Appl. Polym. Sci. 134 (2017) 45238.
[40] L. Peng, Y. Luo, Y. Zheng, W. Zhang, G. Chen, ACS Appl. Nano Mater. 1 (2018) 2219–2226.
[41] K. Feng, L. Peng, L. Yu, et al., ACS Appl. Mater. Interfaces 12 (2020) 27632–27639.
[42] W. Liu, D. Xiao, Z. Tao, A. Dong, ACS Appl. Nano Mater. 5 (2022) 11948–11955.
[43] S.N. Narla, X.L. Sun, Lab Chip 12 (2012) 1656–1663.
[44] S.N. Narla, X.L. Sun, Biomacromolecules 13 (2012) 1675–1682.
[45] C. Pérez-Alonso, F. Lasala, L. Rodríguez-Pérez, et al., ACS Appl. Mater. Interfaces 17 (2025) 10292–10304.
[46] C. Gao, S. Muthukrishnan, W. Li, et al., Macromolecules 40 (2007) 1803–1815.
[47] H. Huang, M. Liu, D. Xu, et al., Mater. Sci. Eng. C 106 (2020) 110157.
[48] S. De Munari, S. Sandoval, E. Pach, et al., Inorg. Chim. Acta 495 (2019) 118933.
[49] S.Y. Hong, G. Tobias, K.T. Al-Jamal, et al., Nat. Mater. 9 (2010) 485–490.
[50] A. Singh, J.C. Arango, A. Shi, J.B. d'Aliberti, S.A. Claridge, J. Am. Chem. Soc. 145 (2023) 1668–1677.
[51] J. Zhao, M. Lu, H. Lai, et al., Biomacromolecules 19 (2018) 481–489.
[52] E.C. Woods, N.A. Yee, J. Shen, C.R. Bertozzi, Angew. Chem. Int. Ed. 54 (2015) 15782–15788.
[53] C.L. Wardzala, Z.S. Clauss, J.R. Kramer, Front. Cell Dev. Biol. 10 (2022) 952931.
[54] Y. Gu, B. Liu, Q. Liu, et al., ACS Appl. Mater. Interfaces 11 (2019) 47720–47729.
[55] Q. Liu, S. Jiang, B. Liu, et al., ACS Macro Lett. 8 (2019) 337–344.
[56] L. Yu, R. Feng, L. Zhu, et al., Sci. Adv. 6 (2020) eabb6595.
[57] L. Zhu, R. Feng, G. Chen, et al., ACS Appl. Mater. Interfaces 14 (2022) 4921–4930.
[58] Y. Zhong, L. Xu, C. Yang, et al., Nat. Commun. 14 (2023) 7285.
[59] J. Mo, Y. Zou, B.-H. Li, et al., ACS Appl. Mater. Interfaces 15 (2023) 40201–40212.
[60] G.L. Koons, M. Diba, A.G. Mikos, Nat. Rev. Mater. 5 (2020) 584–603.
[61] F. Borrull, P.A.G. Cormack, A. Corrigan, et al., Polym. Chem. 16 (2025) 751–761.
[62] T.J. McKenzie, N. Ayres, ACS Omega 8 (2023) 20178–20195.
[63] X. Chen, W. Yuan, M. Jiang, X. Xie, New J. Chem. 42 (2018) 2104–2112.
[64] J. Xiao, Q. Lu, H. Cong, Y. Shen, B. Yu, Polym. Chem. 12 (2021) 6050–6070.
[65] M. Kaupp, A.P. Vogt, J.C. Natterodt, et al., Polym. Chem. 3 (2012) 2605–2614.
[66] W.L. Li, P. Fu, C.Y. Zhu, et al., ACS Appl. Polym. Mater. 5 (2023) 5544–5554.
[67] A. Elizalde-Cárdenas, R.M. Ribas-Aparicio, A. Rodríguez-Martínez, et al., Int. J. Biol. Macromol. 262 (2024) 129999.
[68] M. Ogata, R. Anazawa, L. Connolly, et al., ACS Appl. Mater. Interfaces 16 (2024) 56031–56040.
[69] P. Singh, S. Pandit, S.R. Balusamy, et al., Adv. Healthc. Mater. 13 (2024) 2403059.
[70] M.B. Almeida, C.M.R. Galdiano, F.S.R.d. Silva Benvenuto, E. Carrilho, L.C. Brazaca, ACS Appl. Mater. Interfaces 16 (2024) 67054–67072.
[71] Y. Miura, Y. Hoshino, H. Seto, Chem. Rev. 116 (2015) 1673–1692.
[72] S. Zhang, Y. Hang, J. Wu, et al., ACS Appl. Mater. Interfaces 12 (2020) 22066–22073.
[73] S.M. Dadfar, K. Roemhild, N.I. Drude, et al., Adv. Drug Deliv. Rev. 138 (2019) 302–325.
[74] K. Babiuch, R. Wyrwa, K. Wagner, et al., Biomacromolecules 12 (2011) 681–691.
[75] M. Bloemen, W. Brullot, T.T. Luong, et al., J. Nanopart. Res. 14 (2012) 1100.
[76] T. Nagatsuka, H. Uzawa, K. Sato, et al., ACS Appl. Mater. Interfaces 4 (2012) 832–837.
[77] C. Boyer, M.R. Whittaker, V. Bulmus, J. Liu, T.P. Davis, NPG Asia Mater. 2 (2010) 23–30.
[78] C. Liu, C. Tian, J. Guo, et al., ACS Appl. Mater. Interfaces 16 (2024) 43156–43170.

[79] D. Wang, H. Yao, J. Ye, et al., Small 20 (2024) 2404350.
[80] C.V. McGuire, R.S. Forgan, Chem. Commun. 51 (2015) 5199–5217.
[81] P. Samanta, S. Let, W. Mandal, S. Dutta, S.K. Ghosh, Inorg. Chem. Front. 7 (2020) 1801–1821.
[82] L. Chen, S. Zhang, Y. Duan, et al., Chem. Soc. Rev. 53 (2024) 1167–1315.
[83] N. Namdar, B. Nayeri Fasaei, P. Shariati, S.M. Joghataei, A. Arpanaei, Sci. Rep. 14 (2024) 29242.
[84] H. Chen, Y. Chen, H. Sheardown, M.A. Brook, Biomaterials 26 (2005) 7418–7424.
[85] H. Seto, Y. Ogata, T. Murakami, Y. Hoshino, Y. Miura, ACS Appl. Mater. Interfaces 4 (2011) 411–417.
[86] Y. Terada, W. Hashimoto, T. Endo, et al., J. Mater. Chem. B 2 (2014) 3324–3332.
[87] N. Lawrentschuk, N.E. Fleshner, D.M. Bolton, J. Endourol. 24 (2010) 905–913.
[88] C. Gu, F. Shan, L. Zheng, et al., J. Mater. Chem. B 10 (2022) 1434–1441.
[89] M.L. Huang, M. Cohen, C.J. Fisher, et al., Chem. Commun. 51 (2015) 5326–5329.
[90] D.J. Valles, Y.S. Zholdassov, J. Korpanty, et al., Angew. Chem. Int. Ed. 60 (2021) 20350–20357.
[91] S.J. Malode, S. Pandiaraj, A. Alodhayb, N.P. Shetti, ACS Appl. Bio Mater. 7 (2024) 752–777.
[92] X. Yuan, X. Zhang, L. Sun, Y. Wei, X. Wei, Part. Fibre Toxicol. 16 (2019) 18.
[93] P. Wu, X. Chen, N. Hu, et al., Angew. Chem. Int. Ed. 47 (2008) 5022–5025.
[94] H.G. Sudibya, J. Ma, X. Dong, et al., Angew. Chem. Int. Ed. 48 (2009) 2723–2726.
[95] P.S. Omurtag Ozgen, S. Atasoy, B. Zengin Kurt, et al., J. Mater. Chem. B 8 (2020) 3123–3137.
[96] A.M. DiLillo, K.K. Chan, X.L. Sun, G. Ao, Front. Chem. 10 (2022) 852988.
[97] G. Li, Y. Dao, J. Mo, et al., CCS Chem. 4 (2022) 1930–1937.
[98] D. Rabuka, M.B. Forstner, J.T. Groves, C.R. Bertozzi, J. Am. Chem. Soc. 130 (2008) 5947–5953.
[99] X. Heng, R. Feng, L. Zhu, et al., Chin. Chem. Lett. 33 (2022) 4331–4334.