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REVIEW

Exploring the Frontier of Biopolymer-Assisted Drug Delivery: Advancements, Clinical Applications, and Future Perspectives in Cancer Nanomedicine

Hanan M Alharbi

Department of Pharmaceutical Sciences, College of Pharmacy, Umm Al-Qura University, Makkah, Saudi Arabia

Correspondence: Hanan M Alharbi, Department of Pharmaceutics, Faculty of Pharmacy, Umm Al-Qura University, Makkah, 21955, Saudi Arabia, Email hmsharbi@uqu.edu.sa

Abstract: The burgeoning global mortality rates attributed to cancer have precipitated a critical reassessment of conventional therapeutic modalities, most notably chemotherapy, due to their pronounced adverse effects. This reassessment has instigated a paradigmatic shift towards nanomedicine, with a particular emphasis on the potentialities of biopolymer-assisted drug delivery systems. Biopolymers, distinguished by their impeccable biocompatibility, versatility, and intrinsic biomimetic properties, are rapidly ascending as formidable vectors within the cancer theragnostic arena. This review endeavors to meticulously dissect the avant-garde methodologies central to biopolymer-based nanomedicine, exploring their synthesis, functional mechanisms, and subsequent clinical ramifications. A key focus of this analysis is the pioneering roles and efficacies of lipid-based, polysaccharide, and composite nanocarriers in enhancing drug delivery, notably amplifying the enhanced permeation and retention effect. This examination is further enriched by referencing flagship nano formulations that have received FDA endorsement, thereby underscoring the transformative potential and clinical viability of biopolymer-based nanomedicines. Furthermore, this discourse illuminates groundbreaking advancements in the realm of photodynamic therapy and elucidates the implications of advanced imaging techniques in live models. Conclusively, this review not only synthesizes current research trajectories but also delineates visionary pathways for the integration of cutting-edge biomaterials in cancer treatment. It charts a course for future explorations within the dynamic domain of biopolymer-nanomedicine, thereby contributing to a deeper understanding and enhanced application of these novel therapeutic strategies.

Keywords: theragnostic, nanomedicines, antitumor, drug delivery, nanotherapeutic, anticancer, biopolymers

Introduction

The meteoric rise of cancer as a dominant driver of global mortality underscores the urgent need for action in healthcare initiatives and scientific inquiry. Predictions forewarned of a staggering 10 million cancer-related fatalities in 2020 alone, with the World Health Organization suggesting a potential tripling of this statistic by 2040.[1–3] Most strikingly, 70% of these fatalities occur in low- to middle-income nations, mirroring shifts in lifestyle paradigms. Contemporary cancer interventions, such as chemotherapy, surgery, radiation, immunotherapy, and hormone therapy, are associated with a gamut of side effects.[4–6] The notorious side effects of chemotherapy, ranging from myelotoxicity to cardiotoxicity, stem from non-specific delivery and the amplification of unintended cellular damage.[7–11] This provides a clear indication of the pressing need for precision-focused anticancer drugs. Within this backdrop, nanomedicine has emerged not merely as an alternative, but also as a transformative vector in pharmaceutical research, especially within the drug delivery spectrum.[10–14]

Nanomaterials are revolutionizing cancer therapy by offering novel and more effective treatment options. Their unique properties, such as small size, large surface area-to-volume ratio, and the ability to engineer their surface for specific targeting, make them ideal candidates for cancer treatment applications. Nanomaterials are used in various forms, including nanoparticles, nanoshells, and quantum dots, each serving distinct purposes in cancer therapy. For instance, they are employed to deliver drugs directly to tumor cells, significantly reducing the side effects associated with traditional chemotherapy by

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minimizing drug exposure to healthy cells. Additionally, nanomaterials are utilized in thermal therapy, where they are engineered to absorb specific wavelengths of light, heating up and destroying cancer cells with minimal damage to surrounding tissues. They also play a crucial role in diagnostic applications, enhancing the sensitivity and specificity of cancer detection methods through improved imaging techniques. Furthermore, the integration of diagnostic and therapeutic functions, known as theranostics, exemplifies a significant advancement in personalized medicine, allowing for targeted cancer treatment based on real-time monitoring of the tumor environment. Overall, the application of nanomaterials in cancer therapy holds great promise for improving treatment outcomes, reducing side effects, and paving the way for more personalized and efficient cancer care.[1,15] Biopolymers, with particle sizes ranging from 10 to 1000 nm, have become the epicenter of this research revolution owing to their biocompatibility, design flexibility, and intrinsic biomimetic attributes.[16,17] Recent studies have underscored the promise of naturally derived nanomedicines, from lipid nanocarriers for targeted drug delivery[14,18–21] to sophisticated composite nanocarriers, owing to their heightened specificity and bioavailability.[11–14,16] However, their synthetic counterparts invite skepticism because of their potential cytotoxicities.[22–24]

Historically, the fusion of polymer conjugates with nanomedicine has been the mainstay of research to facilitate precision-targeted drug delivery.[25–29] This narrative is accentuated by innovative strides such as polylactic acid conjugates envisioned for superior drug penetration.[30–33] The intersection of diagnostic and therapeutic methodologies, fortified by biopolymer advancements, heralds an era of unprecedented potential in cancer nanotechnology and synergy spanning biology, chemistry, engineering, and medicine (as depicted in Figure 1). This evolution is crystallized by FDA-approved, nanotech-inspired anticancer marvels such as non-PEGylated liposomal doxorubicin (Myocet), liposomal daunorubicin (DaunoXome), PEGylated liposomal doxorubicin (Doxil), and protein-bound paclitaxel (Abraxane).[34–41]

This review elucidates the complexity of nanodrug formulations, highlights pivotal biomaterials at play, and demonstrates the intricacies of photodynamic therapy and in vivo imaging techniques. Central to the discourse is the aspiration to develop groundbreaking biomaterials for oncological applications, ultimately presenting a blueprint for the future of cancer therapeutics.

Biopolymeric Nanoparticles: Pioneering Next-Generation Drug Delivery Systems (DDS)

Nanotechnology is a beacon in the ever-evolving landscape of therapeutic interventions, particularly in the domain of drug delivery. The incorporation of nanocarriers (NCs) imbued with anticancer agents is rapidly positioning them as game changers, significantly outpacing traditional drug delivery avenues.[42–45] These NCs are designed with utmost precision and serve a dual purpose: they shield encapsulated drugs from untimely degradation and deftly steer them for

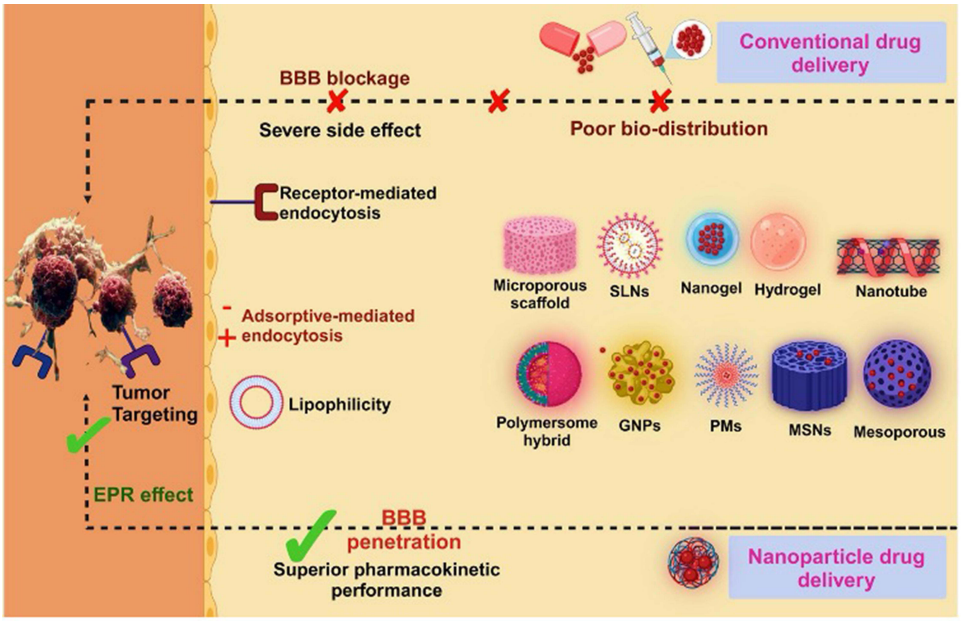

Figure 1 Depiction of biopolymers that improve upon standard drug delivery barriers. EPR boosts the efficiency of tumor destruction (Created with BioRender.com).

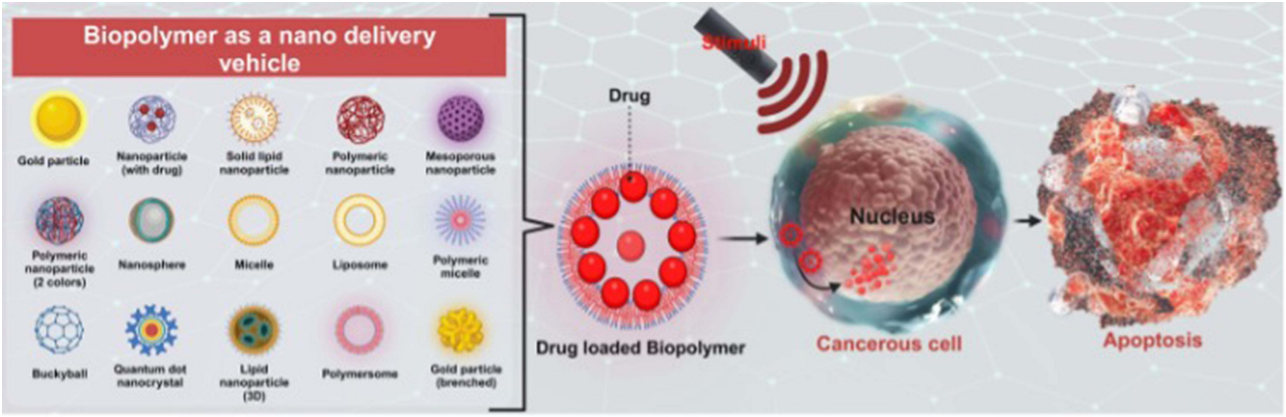

Figure 2 Biopolymers as a potent drug delivery vehicle (Created with BioRender.com).

pinpointed delivery to tumor sites. One of the hallmarks of these NCs is their intrinsic biocompatibility, which enhances their therapeutic efficacy while optimizing its systemic residence.[42–44,46]

This review navigates the intricate world of biopolymers and underscores their significance in the NC-DDS paradigm. Biopolymers, which are natural macromolecules, are distinguished by their nontoxicity, superior biocompatibility, and excellent biodegradability. While the broader family of polymers has consistently anchored NC research, the spotlight is increasingly focusing on natural polymers, such as chitosan, silk, alginate, albumin, starch, and lipids. Their uniqueness lies in their ability to host drugs without requiring chemical modifications, thereby preserving the intrinsic attributes of the drug (Figure 1).[46,47]

Recent advancements in biopolymer nanoparticle synthesis have ushered in a transformational era. Researchers are now armed with several state-of-The-art formulation techniques, each tailored to produce nanoparticles that embody precision and enhance the therapeutic potency against malignant cells. An in-depth analysis of biopolymer as drug delivery vehicle in Figure 2 and Table 1. This detailed matrix contrasts various formulation methodologies with the ensuing particle size, defining their specific biomedical applications, thus offering a holistic perspective on the future trajectory of biopolymeric nanoparticles.[35–40,48–51]

Liposome-Based Biopolymers: Pioneering a New Era in Advanced Drug Delivery Systems

As the pharmaceutical landscape undergoes transformative changes, the introduction of organic polymers, specifically lipid-based biopolymers, is a defining milestone in the evolution of cutting-edge DDS.[51,52] This meteoric rise to prominence can be attributed to their unparalleled compatibility with several therapeutic agents, ranging from hydrophobic to hydrophilic moieties.[53–56]

Liposomes are often heralded as the crown jewels of lipid biopolymers and are characterized by concentric lipid bilayers that encompass an aqueous core. Because of their nanoscale architecture and efficient encapsulation capabilities, they are trailblazers for targeted drug delivery. Their prowess lies in their ability to use therapeutics directly at the diseased site, curtail adverse systemic effects, and bolster therapeutic outcomes.

Table 1 Formulation Techniques and Their Impact on Biopolymeric Nanoparticle Dimensions

Formulation Technique	Average Particle Size (nm)	Notable Biomedical Applications
Emulsion-Solvent Evaporation	50–200	Targeted Drug Delivery, Imaging
Nanoprecipitation	30–150	Gene Delivery, Tumor Therapy
Coacervation	100–300	Enzyme Immobilization, Controlled Drug Release
Electrospray	40–180	Tissue Engineering, Protein Delivery
Microfluidic Synthesis	20–120	Precision Medicine, Diagnostics

Emerging from the shadows of traditional carriers, solid lipid nanoparticles (SLNPs) with their unique solid lipid core are becoming next-generation platforms for delivering water-insoluble therapeutics. Their stability, combined with their controlled release capabilities, positions them as formidable players in the treatment of oncological and neurodegenerative conditions.[57]

Diving deeper into the realm of lipid-based polymers, Weiss et al embarked on pioneering research illuminating the prospects of lipid materials, notably stearic acid-modified polyglycerol adipate, as suitable vectors for drug administration.[54] Their groundbreaking investigations illuminated a paradigm shift from traditional surfactants to innovative coating methodologies, particularly those employing N-(2-hydroxypropyl) methacrylamide copolymers.[54] Notably, although these nanoparticles maintained their structural coherence, they showed discernible fluctuations in their zeta potentials, suggesting nuanced interaction dynamics when interfaced with biological entities.[54] By adding layers of nuance, Weiss et al further augmented their research narrative using an ingenious dual-labeling technique. Harnessing the fluorescence properties of DiR and DYOMICS-676 allows intricate biodistribution investigations, leveraging the advantages of multispectral optical imaging. In parallel to these innovations, age-old formulation strategies have been reinvigorated in the pharmaceutical arena. The venerable spray-drying technique, for instance, is undergoing contemporary metamorphosis, with electrohydrodynamic atomization at its helm, propelling drug solubilization and bioavailability into new dimension.[58–61] (Figure 3 and Table 2)

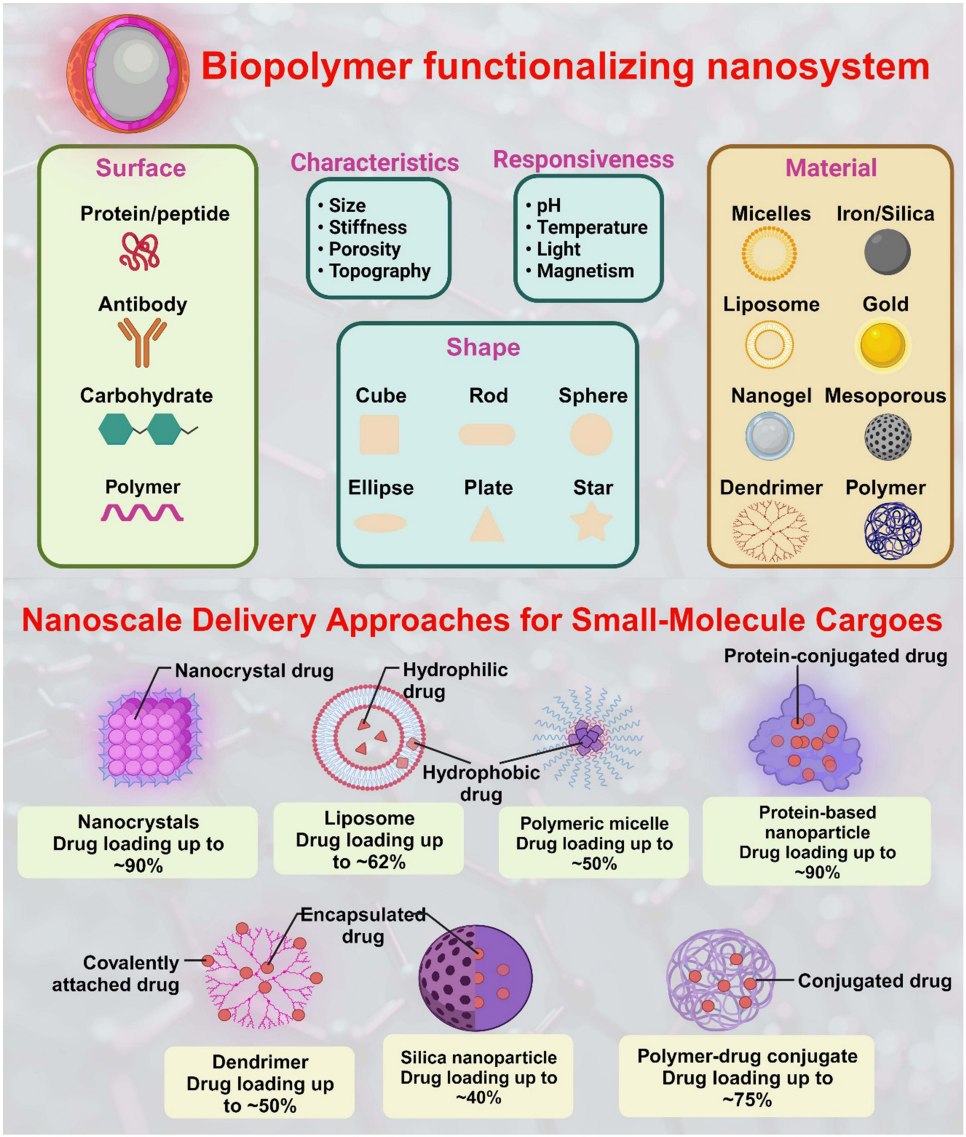

Figure 3 Varieties of Biopolymers and Their Associated Nanoscale Systems (Created with BioRender.com).

Table 2 Comprehensive Analysis of Lipid-Based Biopolymers in DDS

Parameters	SLNPs	Liposomes	Recent Innovations
Composition	- Solid lipid core- Stabilizers- Emulsifiers	- Phospholipid bilayers- Cholesterol (for stability)- Aqueous core	- Stearic acid-modified polyglycerol adipate (PGAS)
Key Attributes	- High encapsulation efficacy- Prolonged release- Enhanced stability	- Biocompatibility- Flexibility in encapsulating both hydrophilic and hydrophobic drugs- Membrane fusion capabilities	- Shifts in zeta-potentials- Dual fluorescence labeling for bio-distribution studies
Application Scope	- Targeted drug delivery- Controlled release- Gene therapy	- Vaccine delivery- Transdermal delivery- Immune response modulation	- Enhanced drug solubilization- Bioavailability augmentation
Technological Adaptations	- Lyophilization for long-term storage- Scale-up production methodologies	- Stealth liposomes to evade immune system- Liposome-drug conjugates	Electro hydrodynamic atomization techniques- non-conventional surfactant replacements
Clinical Implications	- Diminished systemic toxicities- Improved pharmacokinetics- Extended therapeutic windows	- Specific cellular targeting- Reduced adverse effects due to targeted delivery- Therapeutic potentiation	Comprehensive bio-distribution studies- Tailored release profiles

Advancements in lipid nanoparticles (NPs) in DDS have led to a paradigm shift in their therapeutic applications. Zhen et al showed the efficacy of integrating crystalline lipids with photosensitive agents, offering groundbreaking insights into nano-theragnostic modalities.[56] However, inconsistencies in drug release at oncological sites have created challenges. To address these issues, innovative approaches have been proposed.

One noteworthy technique is ultrasonography. Nahire et al demonstrated that lipid nanocarriers in a milieu of cytosolic glutathione yielded an impressive 76% targeted drug release.[57] Remarkably, the efficiency increased to 96% upon exposure of the nanocarrier to a 3-MHz frequency for a concise duration of two minutes. These findings underscore the dual capabilities of lipid NPs in therapeutic drug delivery and potential ultrasound imaging applications contingent on specific environmental modulations.[57] However, the use of lipid NPs is challenging. Although intrinsically favorable for therapeutic delivery, they occasionally encounter issues such as quality control discrepancies and self-assembly formulation variances, potentially undermining their therapeutic impact at designated sites.[58,59] In response, sophisticated techniques integrating electrospray ionization mass spectrometry fragmentation with matrix-assisted laser desorption/ionization and time-of-flight mass spectrometry have been conceived.[60,61] These avant-garde methods facilitate the synthesis of phospholipid peptide bio-conjugates, effectively circumventing unwanted hydrolyzed byproduct formation and ensuring that the therapeutic potency of polymorphic nanotherapeutics remains uncompromised.[62,63] However, the rate of this innovation remains unclear. Novel DDS methodologies have emerged to address concerns, such as unpredictable burst release from certain nanocarriers. A pivotal breakthrough was the development of stimuli-responsive carriers. Stollzoff et al introduced a lipid-coated nanoparticle with intrinsic pH sensitivity that exhibited substantial expansion under select acidic conditions, notably in a lipid environment.[63] Strategic incorporations, such as folic acid and folate receptor targeting, further refine these carriers, enhancing both potency and drug uptake.[61–63] Complementing these findings, Kang et al synthesized PEGylated nanocarriers using hydroxyethyl starch and further refined them using mannose to precisely target dendritic cells.[64] This ingenious approach, when combined with human plasma interactions and specific protein adsorption patterns, demonstrated exceptional targeting efficacy. In summary, lipid-based biopolymers have emerged as indispensable assets for modern drug delivery systems. As research and technology continue to evolve, this domain has been poised for even greater advancement, ensuring unparalleled therapeutic efficacy and precision.

The realm of nanotechnology has undergone significant advancements, particularly in the development of nanocarriers for drug delivery systems. Contemporary research is now focused on the exploration of self-organizing assemblies in conjunction with the intricate phase structures of amphiphilic polymer NPs. This approach is promising for the meticulous design and development of state-of-The-art nanocarriers.[60–65]

One pioneering study in this sphere is by Angyarkanny et al, where they ventured into the realm of micelle assemblies, specifically employing lauryl esters of tyrosine (LET) as a foundation, subsequently coated with polymer nanoparticles. The crafted assemblies showed potential as nanocarriers, particularly for the model solid lipid stearyl alcohol.[66] A pivotal finding of their study was the spontaneous separation of amino acid surfactant dispersions in unadulterated LET and the lauryl esters of phenylalanine micelles. This phenomenon indicates negligible encapsulation of the amino acid surfactant within the micelles.[66–69] Further analyses confirmed that these polymer-enveloped LET micelles were adept matrices for stearyl alcohol encapsulation. The efficacy of this mechanism is fundamentally rooted in the hydrogen-bonding interplay between the phenolic group intrinsic to LET and the hydroxyl group inherent in stearyl alcohol.[66–69]

In parallel, burgeoning interest has been noted among researchers in harnessing the potential of natural silk for nanoparticle development, particularly in the field of oncology. A seminal study by Seib et al encapsulated this ethos. Their detailed exploration involved in vitro trials with silk NPs imbued with the anticancer drug, doxorubicin. The results indicated that silk NPs evinced discernible non-toxicity toward healthy cells while concurrently surmounting inherent drug resistance mechanisms, showcasing their profound therapeutic potential.[70]

The continuous evolution and expansion of research in this field underscores the vast potential of self-assembled structures, especially when paired with polymer NPs, to revolutionize drug delivery and cancer therapy. As the body of research grows, it becomes imperative to remain at the forefront, to embrace, and drive innovations that can redefine therapeutic interventions (Table 3).

Harnessing the Potential of Polysaccharide-Based Biopolymers for Advanced Drug Delivery Systems

The nexus of contemporary pharmaceutical research lies in the pivotal role of polysaccharides with their intrinsic biocompatibility, minimal toxicity, and unparalleled stability. These attributes make them indispensable cornerstones of the architecture of stimulus responsive DDS.[74] Among these polysaccharides, alginates and chitosan have a distinctive niche, demonstrating exemplary utility in DDS, either in their pristine form or following meticulous surface modifications.[74,75]

Diving deeper into formulation techniques, Wang et al unveiled pioneering manufacturing strategies, laying the foundation for the design of high-potential biopolymers such as polylactic acid and chitosan nanoparticles, earmarked for nanomedical applications.[76] A notable example is the Emulsion Diffusion Method, which is optimized for both hydrophilic and lipophilic agents. Concurrently, the synthesis of chitosan nanoparticles has been enhanced through approaches such as ionic gelation and the avant-garde reverse micelle technique. These nanoparticles with post-advanced surface modifications, including hydrophilicity augmentation and chitosan functionalization, have shown outstanding results in rigorous in vivo evaluations.[76]

Illuminating the nuanced behavior of polysaccharides, Alvarez-Lorenzo et al highlighted the pH-responsive nature of ionic variants, such as chitosan, which makes them swell in acidic milieus and contract in neutral or alkaline

Table 3 Surface Modifications of Nanoparticles by Biopolymers for Enhanced Drug delivery

Nanoparticle	Biopolymers	Drug	Biomedical Applications
PEG	Lipid	Paclitaxel	In vitro uptake enhanced
Hydroxylated ethyl starch	PEG layer and mannose	N/A	Targeting dendritic cells
MMT clay	Starch/D-L-lactic acid	Dimethyl sulfoxide (DMSO)	In vitro studies revealed a sustained release
Gold nanoparticles	Gelatin	Doxorubicin	In vitro studies revealed a sustained release
Gold nanorods	Lipids	N/A	Enhanced bio-imaging

Note: Data from.[69–73]

environments.[77] These inherent traits indicate that these polysaccharides are prime candidates for precision-targeted oral drug delivery, particularly targeting the colon. Furthermore, discernible pH variations between benign and malignant cells offer a platform for creating stimulus-activated carriers that can dictate drug release kinetics when synergized with external stimuli encompassing light and temperature gradients.

Further enriching the research spectrum, Kim et al created chitosan-coated magnetic nanoparticles for applications in hyperthermic treatments.[78] Conversely, Alkanawati et al made pioneering strides in optimizing laboratory-scale nano-carrier production, setting new benchmarks for quality and scalability.[79] With imaging agents in their arsenal, polysaccharides are poised to redefine the paradigm of drug delivery and guided chemotherapy.[74–78] Starch, a cost-effective and biocompatible alternative, is emerging as the vanguard for DDS. Contemporary research endeavors are geared toward increasing stability and functional performance. By leveraging state-of-The-art synthesis methodologies such as self-assembly via reversible fragmentation chain transfer addition or anionic polymerization, researchers are approaching optimal nanocarrier designs.[76–79]

The efficacy of nanomaterials, bolstered by their precision-targeting attributes, positions them several notches above traditional chemotherapeutic agents. The ongoing research trajectory is rife with efforts to elevate the penetration efficacy of these nanoparticles, employing avant-garde cross-linking techniques. Ren et al, through their seminal work, underscored the myriad advantages of nanomedicine, encompassing effortless preparation, heightened drug encapsulation, and enhanced stability.[80] Pathbreaking methodologies, like eco-centric 'graft copolymerization-induced self-assembly', are redefining the synthesis paradigm for nano-carriers.[81] Moreover, the emergent technique of electrospinning, harnessing electrohydrodynamic forces, promises to create nanoparticles poised for precision drug release in oncological interventions (Table 4 and Figure 4).

Exosomes: The Vanguard of Innovative Drug Delivery Systems

Exosomes, nature's finely crafted nanoscale vehicles, ranging between 30–150 nm in size, emanate from the endosomal compartment of several eukaryotic cells.[86–88] What renders them uniquely intriguing is their eclectic cargo – a harmonious blend of lipids, proteins, mRNAs, and miRNAs. This intrinsic composition allows them to serve as intercellular messengers, mediating a dynamic transfer of vital biomolecules between cells.[86–88] The recent surge in exosome-centric research within the drug delivery spectrum can be attributed to a confluence of their salient features: impeccable biocompatibility, minimal immunogenicity, and a remarkable proficiency to traverse biological impediments. These characteristics position exosomes as optimal carriers for an array of therapeutic agents, spanning drugs, essential proteins, and crucial nucleic acids. A game-changing advantage lies in the modifiable surface of exosomes. By adorning them with specific targeting ligands, researchers can commandeer their trajectory, ensuring they home in with laser-like precision to designated cells or tissues. Amplifying their drug delivery prowess is their innate shield, which meticulously safeguards their cargo against potential enzymatic degradation, thereby augmenting their efficacy as pharmaceutical carriers.[87–89]

The vast expanse of therapeutic arenas, ranging from the labyrinthine world of oncology to the complexities of neurodegenerative maladies, are witnessing pioneering interventions, all leveraging the unparalleled potential of exosomes.[86–89] For a more comprehensive understanding, we present Figure 5; Tables 5 and 6, elucidating various types of exosomes, delineating their sources, their isolation techniques, and their nuanced delivery mechanisms.

Table 4 Nanoparticle Formulation Techniques to Understand the Processes That Provide the Desired Particle Size for Biomedical applications

Techniques	Nanoparticles	Dimension
Electrospinning	Elastin-like polypeptides	110–680 nm
Polymerization under nonlinear sub-structuring	Gelatin core with a quantum dot on the surface	30–100 nm
Low-energy throughput (Mechanical stirring @800 rpm without heat)	PEGylated NP	174 nm–184 nm
Enzymatic synthesis	Polyglycerol adipate	136 nm

Note: Data from.[56–58,80–85]

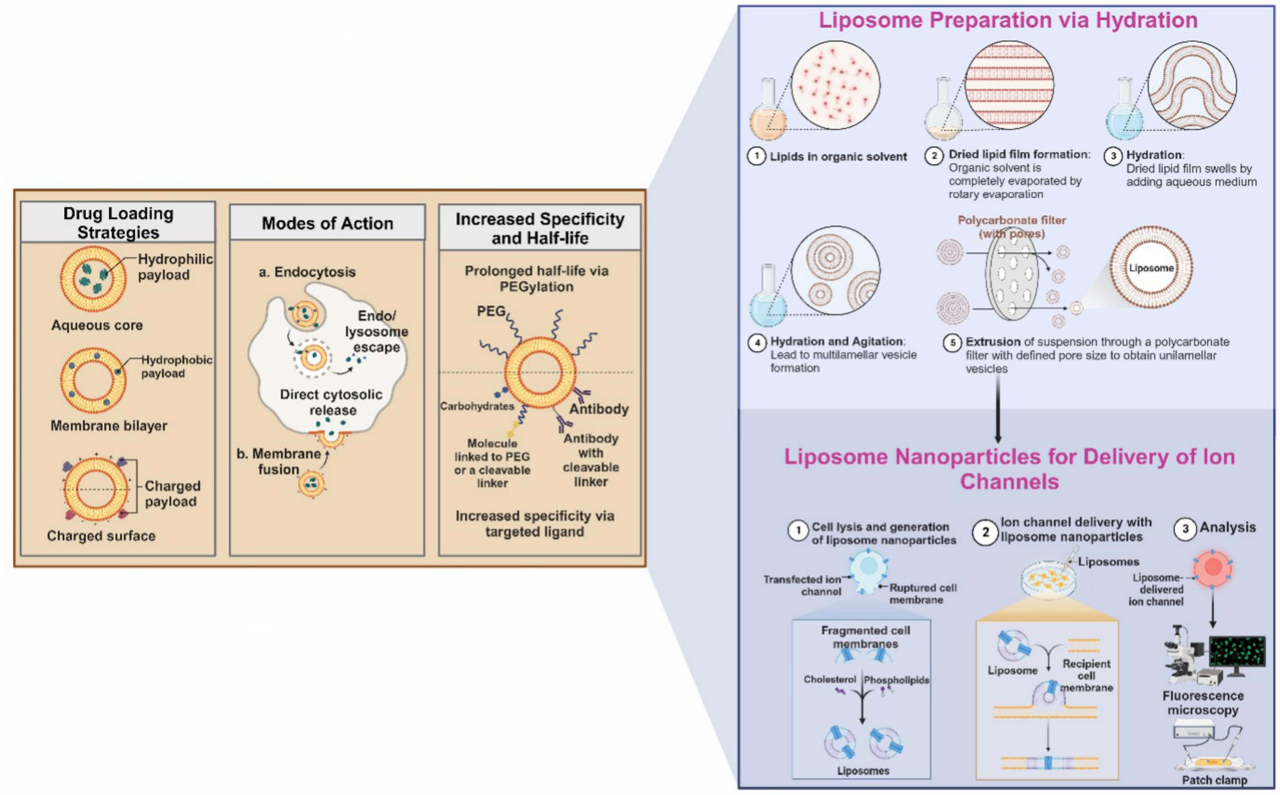

Figure 4 Creating Liposomes and Nanocarriers through Film Hydration and Ion Channel Approaches (Created with BioRender.com).

Advanced Mechanisms in Mesenchymal Stem Cell-Based Biopolymer-Based Drug Delivery Systems

The realm of drug delivery has witnessed transformative advancements in recent years, with a heightened focus on biopolymer applications aimed at optimizing drug bioavailability and precision-targeting specific tumor regions, as visualized in Figures 6 and 7. The growing impetus toward harnessing polymeric materials stems from their inherent attributes that make them superior carriers for drug delivery.[89–92]

Injectable Implant Systems

Pioneering formulations such as injectable implant systems leverage biopolymers in innovative ways. For instance, thermoplastic pastes and thermally induced gelling systems have been engineered to offer nuanced control over drug release while bolstering drug retention properties.[93–95]

Biocompatibility and Biodegradability

The benchmarks for effective nano-carriers are undoubtedly biocompatibility and biodegradability.[94–96] Starch, cellulose, chitosan, albumin, and gliadin stand out as natural polymers that satisfy these stringent requirements.[97] Hydroxyethyl starch, a byproduct of starch modifications, has been adeptly employed to encapsulate doxorubicin, yielding enhancements in drug release rates and extending its circulation duration in the bloodstream—thereby zeroing in on prostate cancer cells with increased efficiency.[97] Gliadin NPs, synthesized through the state-of-The-art electrospinning technique, have been identified as promising carriers for anti-cancer drugs, proficiently targeting breast cancer cells to induce apoptosis.[98]

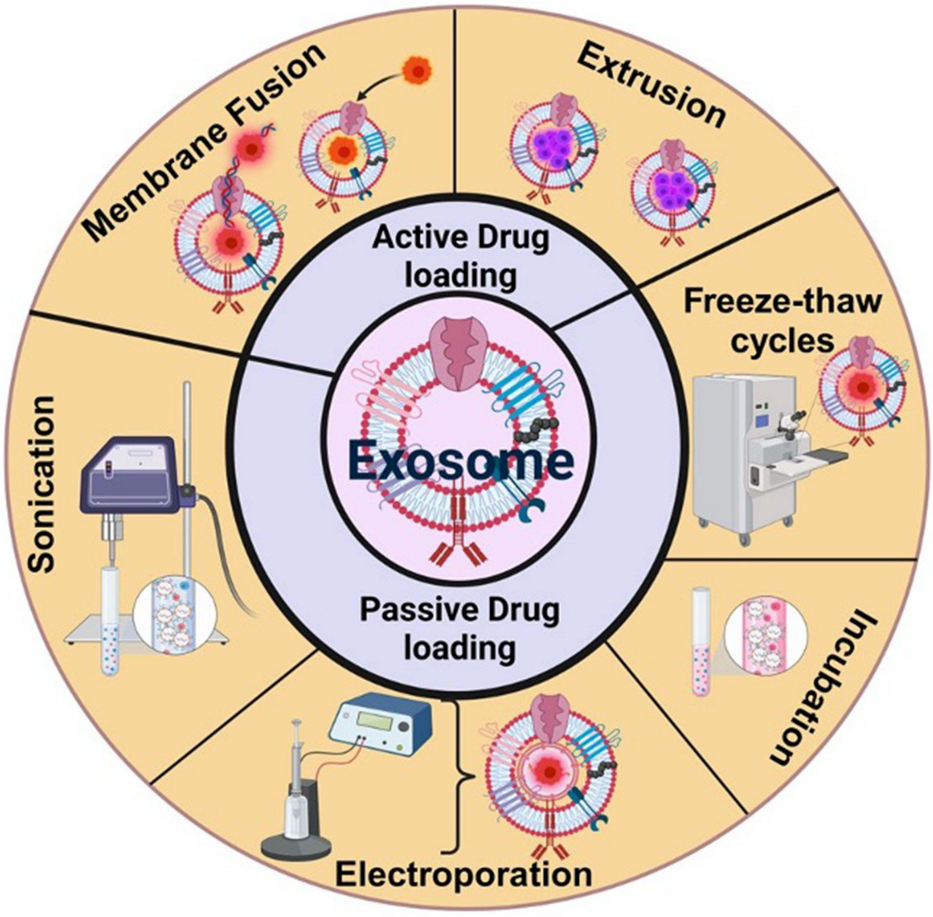

Figure 5 Exosomes-based Drug Delivery Systems to Cancer cells (Created with BioRender.com).

Chitosan's Multifaceted Role

Chitosan, with its origins in the crustacean exoskeleton, has been the subject of intensive research in the drug delivery domain since the early 1990s.[95,96] A noteworthy feature of chitosan is its amphiphilic nature, facilitating nanoparticle formation in aqueous environments without crosslinking agents.[96,99,100] Studies corroborate that chitosan NPs enhance

Table 5 Detailed Overview of Exosomes in Drug Delivery

Feature	Description
Origin	Endosomal compartment of eukaryotic cells
Size	30–150 nm
Cargo	Lipids, proteins, mRNAs, miRNAs
Biological role	Intercellular communication, immune modulation, and waste removal
Sources	- Mesenchymal stem cells - Epithelial cells - Cancer cells - Immune cells (*eg*, T cells, B cells) - Neurons - Blood plasma, urine, saliva, and other bodily fluids
Advantage for drug delivery	- Biocompatible - Low immunogenicity - Ability to cross biological barriers

(*Continued*)

Table 5 (Continued).

Feature	Description
Surface modification	Allows for targeted delivery to specific cells or tissues
Delivery mechanism	- Direct fusion with the plasma membrane - Endocytosis by recipient cells - Receptor-ligand interactions leading to uptake
Application	- Cancer therapies - Regenerative medicine - Vaccination - RNA interference therapies - Enzyme replacement therapy
Challenges	- Scalable isolation and purification - Ensuring consistent content and functionality across preparations - Potential for unintended side effects (*eg*, triggering immune responses or transferring unwanted biomolecules)

Table 6 Exosomal Varieties, Sources, and Delivery Mechanisms

Exosome Type	Source	Isolation Technique	Delivery Mechanism
Type A	Source A	Ultracentrifugation	Endocytosis
Type B	Source B	Size-exclusion chromatography	Fusion with Plasma Membrane
Type C	Source C	Polymeric Precipitation	Direct Fusion
Type D	Source D	Immunoaffinity capture	Micropinocytosis

oral bioavailability for hydrophobic drugs, simultaneously ensuring targeted delivery to tumor sites and mitigating toxic impacts on healthy cells.[96–101]

Silk Fibroin Nanoparticles

A promising frontier in drug delivery pertains to silk fibroin NPs. These NPs exhibit immense potential, especially as carriers for lysosomotropic anti-cancer drugs. Innovative integrations, such as embedding magnetic iron oxide NPs within silk fibroin matrices, have registered significant reductions in tumor growth, concurrently improving survival rates in vivo.[101] Additionally, both chitosan NPs and silk fibroin magnetic NPs have manifested controlled drug release capabilities when subjected to magnetic stimuli, ushering in an era of personalized drug regimens tailored for individual patients.[97]

Advancements in Penetration & Loading

Confronting the challenge of restricted drug penetration within tumors, researchers have architected nano-structured polymeric materials, including aldehyde dextran-doxorubicin conjugates. The adoption of a 3D cell structure paradigm has unveiled intricate drug release mechanisms from these conjugates, specifically advantageous in neuroblastoma treatments.[102] Nano-carrier drug-loading methodologies have been distinctly classified into surface loading, matrix loading, and cavity loading, each equipped with its distinct drug release dynamics.[103] To overcome quantification challenges with hydrophobic nano-carrier-loaded drugs, advanced techniques like fluorescence correlation spectroscopy have been deployed.[104]

Innovative Delivery Methods

The advent of microfluidic channels is unlocking new dimensions in producing nanocrystals within confined environments. While peptide-based nano-carriers have always shown promise, recent strides indicate that encasing these peptides within virus-like structures amplifies their anti-tumor efficacy.[105,106] These structures further engage the immune system, bolstering their prowess as drug-delivery platforms.

The rapid evolution in biopolymer-facilitated drug delivery augurs well for precision-driven cancer treatments. By marrying sophisticated drug design philosophies with trailblazing nano-carrier fabrication and avant-garde

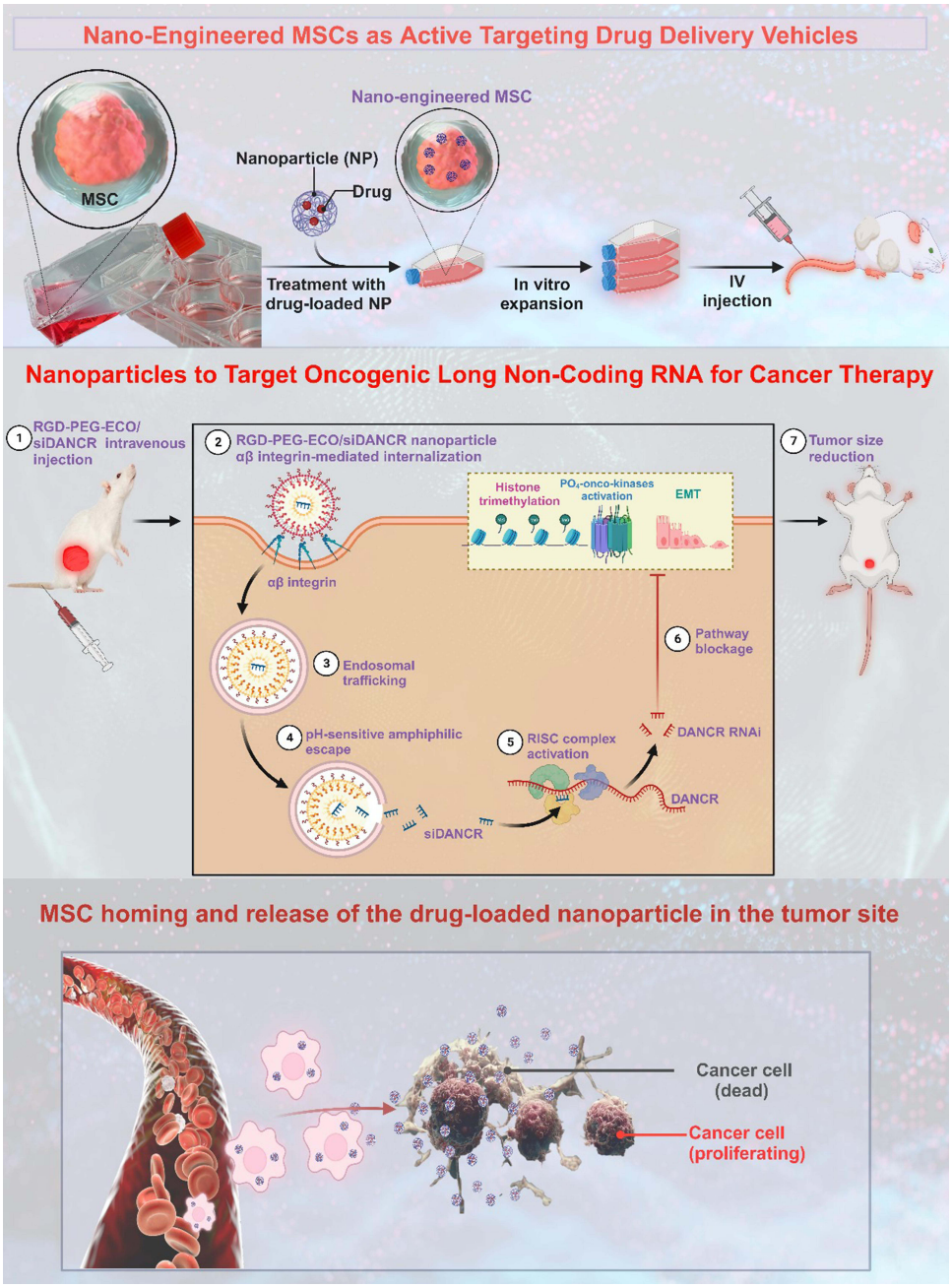

Figure 6 Mesenchymal Stem Cell-based biopolymer delivery and cancer treatments (Created with BioRender.com).

characterization methodologies, the horizon seems promising for bespoke therapeutic solutions in not just oncology, but a broader spectrum of diseases.

Application of Biopolymers for Active Targeting of Cancer Cells and Therapy

Cancer, with its pervasive presence globally, is synonymous with high mortality rates and necessitates the evolution of effective therapeutic strategies that mitigate side effects. Traditional chemotherapy, while efficacious, remains controversial due to its indiscriminate nature—targeting both malignant and healthy cells. Herein lies the growing interest in biopolymers as a groundbreaking alternative. With innate characteristics like biocompatibility and biodegradability, biopolymers pave the way for a new generation of theragnostic tools for enhanced active and passive targeting of cancer cells (depicted in Figure 8).

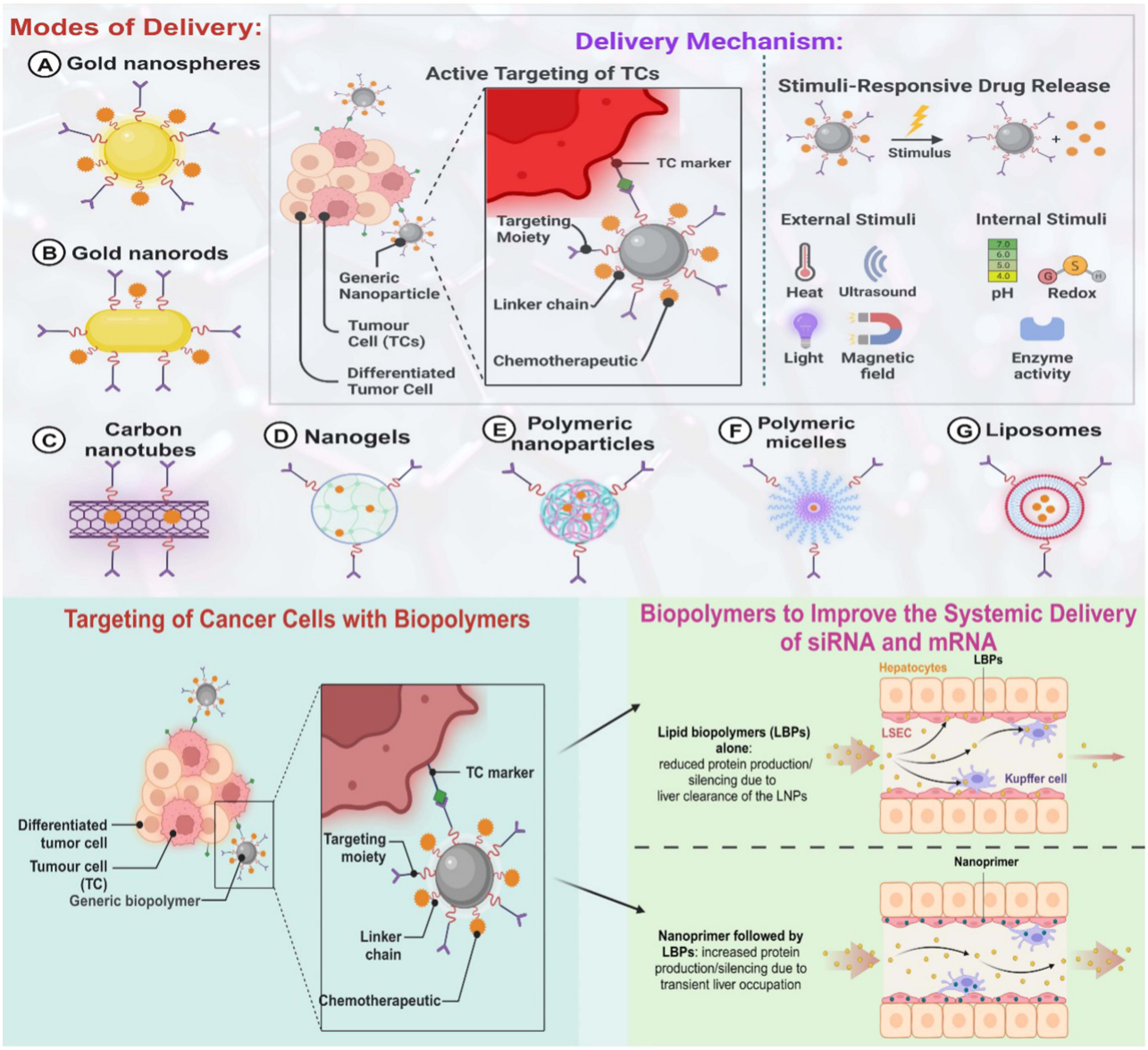

Figure 7 Comprehensive Overview of Nanotechnology in Cancer Therapy and Systemic Delivery of Therapeutic Molecules. Modes of Delivery illustrates various nanomaterials utilized for cancer therapy delivery systems: (**A**) Gold nanospheres and (**B**) Gold nanorods showcasing their potential as carriers due to their stability and ability to be functionalized with targeting moieties, (**C**) Carbon nanotubes, known for their high aspect ratio, allowing them to penetrate cells effectively. (**D**) Nanogels: Highlighted as hydrogel nanoparticles, showcasing their capacity for encapsulating drugs and releasing them in response to specific tumor microenvironment conditions, (**E**) Polymeric Nanoparticles: Illustrated as versatile carriers for drug delivery, capable of being engineered to enhance biocompatibility and targeting efficiency, (**F**) Polymeric Micelles: Demonstrated as nanoscale assemblies useful for solubilizing hydrophobic drugs and targeting tumor sites effectively, (**G**) Liposomes: Presented as spherical vesicles that encapsulate drugs, offering a biocompatible and efficient delivery mechanism.[15] Created with BioRender.com.

Starch-Based Nano-Carriers in Drug Delivery

Starch, a ubiquitous natural polymer, possesses characteristics conducive to drug delivery, including non-cytotoxicity, biocompatibility, and air stability. Dandekar et al innovated by synthesizing a hydrophobic variant of starch, propyl-starch, to encapsulate Docetaxel through solvent emulsification diffusion techniques.[107] Notably, these NPs capitalized on their 'nano-size' attribute to enhance drug efficacy and target cancer cells more effectively.

Protein-Based Nanocarriers - A Revolution

Gliadin, soya, bovine serum albumin (BSA), milk protein, zein, elastin, and gelatin represent a class of proteins showing potential as biopolymeric nanocarriers. Such protein-based NPs utilize the Enhanced Permeability and Retention (EPR)

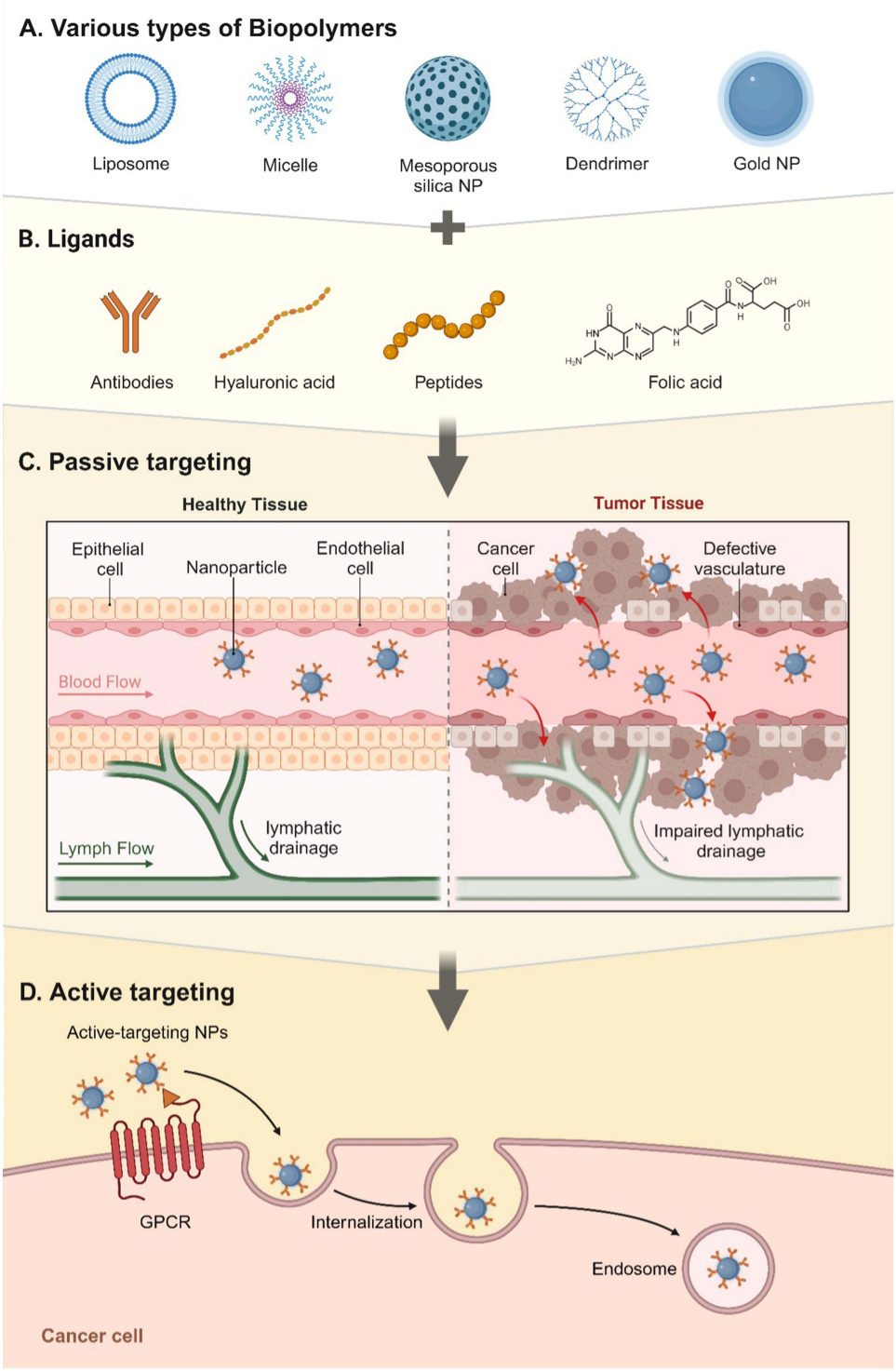

Figure 8 Overview of Biopolymer Applications in Nanomedicine for Cancer Therapy: (**A**) Various Types of Biopolymers: This section illustrates different biopolymer nanocarriers utilized in drug delivery systems, including Liposome, Micelle, Mesoporous silica NP, Dendrimer, and Gold NP, each with unique properties for encapsulating and delivering therapeutic agents, (**B**) Ligands: Depicts common ligands that can be conjugated to biopolymer nanocarriers for targeted drug delivery, including Antibodies, Hyaluronic acid, Peptides, and Folic acid. These ligands enhance the specificity of nanocarriers towards cancer cells by binding to corresponding receptors, (**C**) Passive Targeting: Illustrates the concept of passive targeting where nanoparticles accumulate in tumor tissue more than in healthy tissue due to the Enhanced Permeability and Retention (EPR) effect. This effect is facilitated by the defective vasculature and impaired lymphatic drainage in tumor tissue, allowing nanoparticles to passively target and treat cancer cells; (**D**) Active Targeting: Shows the mechanism of active targeting, where nanoparticles are designed to specifically bind to receptors on cancer cells (eg, GPCR). Upon binding, the nanoparticles are internalized into the cancer cells, allowing for the direct delivery of therapeutic agents into the target cells. This method increases the efficacy and specificity of cancer treatment by ensuring that the drug directly reaches the cancerous cells while minimizing exposure to healthy cells.[15] (Created with BioRender.com).

effect to their advantage. As a result, there is a pronounced drug accumulation at the tumor site, magnifying therapeutic outcomes.[108–110] Furthermore, protein NPs boast of a benign synthesis process, devoid of harmful chemicals and facilitated by methods like coacervation/dissolvation, emulsion solvent extraction, and complex coacervation.[108–110]

Chitosan-Based Drug Delivery Systems

Chitosan, a biopolymer obtained from crustacean exoskeletons, is recognized for its ability to form nanoparticles in aqueous solutions without crosslinking agents.[111] Chitosan NPs stand out for improving the oral bioavailability of hydrophobic drugs and zeroing in on cancer cells while averting healthy ones.

Exploring Albumin-Bound Nano-Carriers

The findings of Lohcharoenkal et al accentuate the potential of proteins in cancer theragnostic. With particle size distribution at around 130 nm, albumin-bound nano-carriers show immense potential.[107] Remarkably, the FDA-approved albumin-bound paclitaxel (Abraxane, ABI-008) is being used to treat metastatic breast cancer, underscoring its clinical feasibility. Cationic bovine serum albumin has emerged as a promising siRNA delivery system for metastatic lung cancer.[101–103]

Role of Lipid-Based Nano-Carriers in Breast Cancer Therapy

Liposomes and micelles, representing lipid-based nano-carriers, have made strides in breast cancer treatment. Andey et al have demonstrated the amplified effectiveness of the lipid-conjugated estrogenic derivative (ESC8) when loaded with cisplatin, especially in a xenograft mouse model.[104–112] Their studies have further shown the potential of lipid nano-carriers in treating drug-resistant cancers.

Hybrid Nano-Carriers - Merging Lipids and Polymers

In pursuit of improved nano-carriers, researchers have merged the best of both worlds: lipids and polymers. These hybrid nano-carriers offer an economical and stable solution, bringing in the benefits of diverse chemical modifications and controlled drug release.[63,109] Date et al have detailed the delivery mechanisms of these hybrid nanomedicines, reinforcing their efficacy in cancer therapy.[113]

Leveraging Polymer Conjugates, Liposomes, and Micelles

Polymer conjugates, liposomes, micelles, and metal NPs have carved a niche for themselves as indispensable nanomedicines for cancer therapeutics. Taurin et al have focused on the EPR effect of tumors on these nanomedicines.[108]

In conclusion, biopolymeric nanoparticles are positioning themselves as the frontrunners in theragnostic applications for cancer treatment. Their multifaceted nature, with the incorporation of proteins, lipids, and polymer conjugates, underscores significant advancements in drug delivery, bioavailability, and targeting capabilities. As we venture further into this field, we are poised to redefine cancer therapeutics, promising personalized and more effective treatments (Table 7 and Figure 9).

Table 7 Examples of Biopolymer-Based Nanocarriers for Anticancer Drug Delivery

Biopolymer	Anticancer Agent	Delivery Technique	Efficacy and Benefits
Propyl-Starch	Docetaxel	Solvent Emulsification	Enhanced drug efficacy and availability within cancer cell lines
Gliadin	Various anticancer agents	Coacervation/Dissolvation	Efficient drug delivery at the nanoscale
Soya	Anticancer drugs	Emulsion Solvent Extraction	Improved therapeutic outcomes through targeted drug delivery
BSA	Doxorubicin	Complex Coacervation	Targeted association with the nucleus (peri/intra)

(*Continued*)

Table 7 (Continued).

Biopolymer	Anticancer Agent	Delivery Technique	Efficacy and Benefits
Zein	Various anticancer agents	Emulsion solvent extraction	Controlled drug release and compatibility with diverse drugs
Elastin	Curcumin	Emulsion solvent extraction	Enhanced stability and sustained release of the therapeutic agent
Gelatin	Paclitaxel	Coacervation	Efficient drug delivery and targeted antitumor activity

Advancements in Nanomedicine for Comprehensive Cancer Treatment Approaches

Combination Therapy: Expanding the Horizons of Cancer Treatment

Combination therapy, which employs multiple therapeutic agents to treat cancer, has emerged as a game-changing approach due to the limitations of traditional monotherapies. The synergy between various agents can amplify the therapeutic effects, address drug resistance, and reduce adverse side effects.

Dual Nanomedicine Combination Therapy

Dai et al emphasized harnessing the benefits of dual nanomedicine therapy.[114] Instead of merely co-delivering multiple drugs using a single nano-carrier, this method integrates distinct nanomedicines or drug-loaded nanocarriers. The merit here is to simultaneously target different facets of cancer biology, thereby augmenting the therapeutic impact.

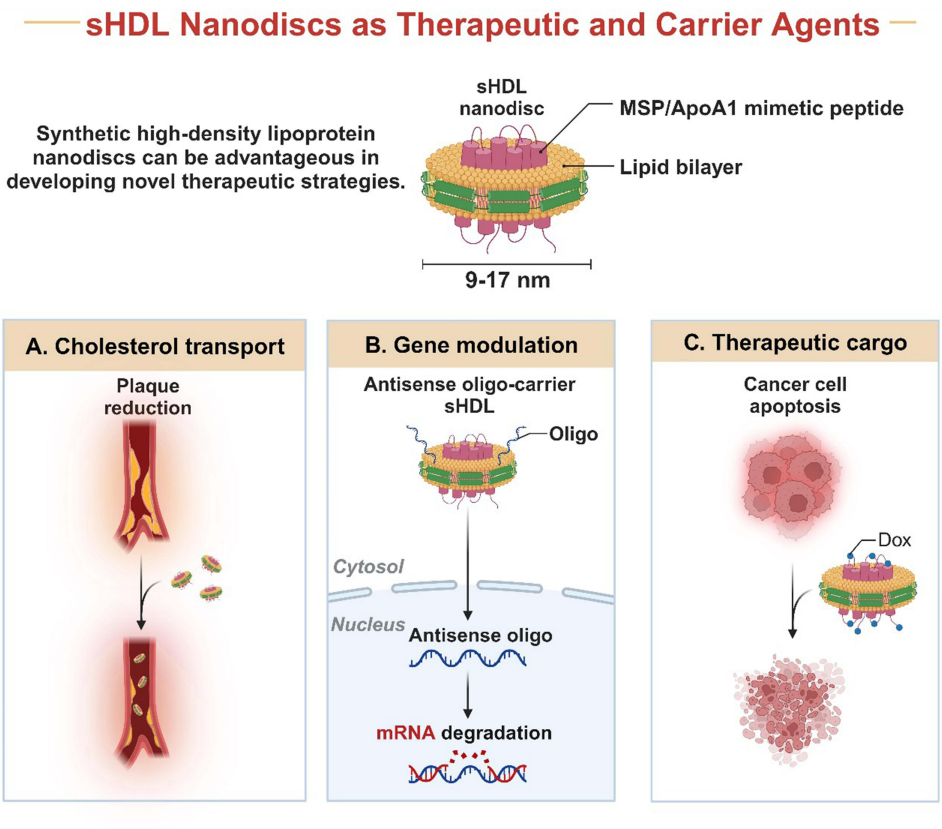

Figure 9 Applications of Synthetic High-Density Lipoprotein (sHDL) Nanodiscs in Medical Therapeutics: (**A**) Cholesterol Transport: Illustrates the role of sHDL nanodiscs in cardiovascular health, specifically in the transport of cholesterol away from plaque sites within arteries, thereby contributing to plaque reduction and the prevention of atherosclerosis, (**B**) Gene Modulation: Depicts the use of sHDL nanodiscs as carriers for antisense oligonucleotides (Oligo), demonstrating their potential in gene therapy. By delivering these oligonucleotides into cells, sHDL nanodiscs can facilitate the degradation of target mRNA in the cytosol, offering a method for modulating gene expression in various diseases, (**C**). Therapeutic Cargo Delivery: The application of sHDL nanodiscs in cancer therapy by delivering therapeutic agents, such as doxorubicin (Dox), directly to cancer cells. This targeted delivery mechanism can induce apoptosis in cancer cells, highlighting the potential of sHDL nanodiscs in enhancing the efficacy and specificity of cancer treatments. Created with BioRender.com.

Active Vs Passive Targeting

The realm of targeted nanomedicines is vast and growing. Passive targeting relies on the natural tendency of nanoparticles to accumulate in tumors due to the EPR effect.[108–110] However, for more precise drug delivery, active targeting can be achieved. By adorning nanocarriers with ligands that specifically bind to receptors abundantly expressed on cancer cells, the therapeutic agents can be directed right where they are needed the most.

Responsive Hierarchical Nanomedicine (HRNM)

The work of Wang et al on HRNM stands out,[115] with a methodology that employs cyclic Arg-Gly-Asp (RGD) peptide-conjugated triblock copolymers, which have been shown to localize effectively within the tumor, with minimal off-target effects.

Novel Approaches in Nano-Carrier Therapeutics

Charge-Convertible Polymers

These unique polymers undergo a charge transformation specifically at the tumor site. Their initial charge, either neutral or negative, gets activated within the tumor milieu, facilitating selective cancer cell death without harming healthy cells.[116]

Nanotextile Implants

For conditions like late-stage ovarian cancer, there is promise in nanotextile implants. These biopolymeric materials, when woven, may serve as controlled drug delivery systems, providing localized therapy and possibly reducing systemic side effects.[117]

Cathepsin-Based Nanodrugs

Cathepsin, an enzyme often implicated in cancer progression, is now at the forefront of targeted therapy research. Nanodrugs designed to exploit this pathway may offer a more direct approach to halting tumor growth.[118]

Photodynamic Therapy (PDT): Shining Light on Cancer Therapy

PDT is gaining traction as an alternative cancer treatment, wherein photosensitizers, when activated by light, generate ROS that can kill cancer cells.

Porphyrin-Based Photosensitizers: When integrated into polymeric nanocarriers, these photosensitizers have shown potential against carcinomas of the breast, lungs, and liver.[118]

Indocyanine Green: This photosensitizer, when combined with other therapeutic agents in nano-formulations, has the potential to optimize the therapeutic outcomes of PDT.[119]

Persistent Luminescence (PersLum): The ability of PersLum materials to continue emitting fluorescence even post-light-source removal may revolutionize PDT efficiency.[119–121]

The Dawn of Advanced Cancer Imaging

High-resolution imaging is pivotal for the early diagnosis and treatment planning of and monitoring therapeutic responses in cancer.

Quantum Dots in Imaging

When linked with specific biomolecules, quantum dots have exhibited exceptional potential in early-stage cancer detection.[122]

Glycol Chitosan-Based Nano-carriers: These nano-carriers, when used in photothermal therapy, combine the merits of therapy and imaging. Their inherent stability and biocompatibility make them ideal candidates.[123]

Gold Nano-Clusters

Gold, when manipulated at the nanoscale, can emit both heat and fluorescence, making it a promising material for combined therapeutic and diagnostic applications.[23,39,124–129]

The burgeoning field of nanomedicine is poised to reshape cancer therapeutics, offering more personalized, precise, and potent treatment modalities. As the frontier of nanomedicine research continues to expand, it brings forth innovations that can profoundly influence patient outcomes, steering us closer to a future where cancer is a manageable, if not curable, condition (Figure 9)

Melanin Nanoparticles: A Promising Nano-Carrier for Image-Guided Chemotherapy in Cancer Therapy

Nano-carriers have emerged as promising theragnostic agents for image guidance in cancer therapy. Among them, melanin nanoparticles (MNPs) have drawn considerable attention as an efficient drug delivery system for image-guided chemotherapy.[124] Melanin, a biopolymer with excellent biological compatibility, degradability, and intrinsic photoacoustic properties, offers a unique advantage in developing endogenous nano DDS for imaging-guided chemotherapy.[124,125]

The formulation of MNPs involves loading them with anticancer drugs, such as sorafenib, to enhance their hydrophilicity and enable drug delivery. The resulting melanin-sorafenib nanoparticles (SRFMNPs) demonstrate strong interactions between the drug and melanin through pi bonding.[98] Notably, SRFMNPs exhibit an equivalent anti-cancer effect compared to traditional polymeric NPs while requiring a lower drug loading dose (4 mg/kg SRF, one time every 2 days for MNPs vs 3 mg/kg SRF, three times every four days for polymeric NPs). This highlights the advantageous nature of the MNP-based drug delivery system, offering comparable antitumor efficacy with reduced drug dosage.

Compared to traditional nano-platforms used in imaging-guided therapy, MNP formulations present several benefits. Traditional platforms often necessitate complex functionalization and the introduction of contrast agents, which may raise concerns about potential toxicity. In contrast, MNPs can be prepared using a simple and straightforward process, making them more suitable for safe and effective imaging-guided therapy[125,126] (Table 8).

Bovine Serum Albumin-Based Nano-Carrier for Fluorescence-Guided Drug Delivery in Cancer Therapy

Recent research has demonstrated the significance of BSA as an efficient nano-carrier for drug delivery with applications in fluorescence studies and noninvasive optical imaging in biomedical fields.[130–132] While BSA alone lacks photoluminescence properties, Pan et al developed a novel nano-drug delivery system (nano-DDS) by doping BSA with gold nanoclusters, iron NPs, and gold nanorods as fluorescence agents.[133] Gold nanorods and clusters are biocompatible, inert, and offer superior photoluminescence compared to conventional photo-bleachable agents, making them excellent

Table 8 Comparison of Traditional Nano-Platforms and Melanin Nanoparticle Formulations for Imaging-Guided Therapy

Aspect	Traditional Nano-platforms	Melanin Nanoparticles (MNPs)
Complexity of Formulation	Complex	Simple
Introduction of Contrast	Yes	No
Potential Toxicity	Possible	Minimal
Biological Compatibility	Varied	High
Biodegradability	Varied	High
Photoacoustic Properties	Depends on contrast agent	Intrinsic
Drug-binding Capability	Limited	High
Antitumor Effect	Comparable	Equivalent or better

fluorescent probes for in vivo imaging within the near-infrared (NIR) "biological window" between 650−900 nm.[134] The incorporation of gold nanorods, nanoclusters, and iron NPs into BSA-based nano-DDS opens up a wide variety of possibilities for disease detection imaging using techniques such as magnetic resonance imaging (Figure 10 and Table 9).

Furthermore, the combination of doxorubicin with this nano-carrier exhibited efficient delivery to hepatocarcinoma cells, leading to significant apoptosis. The photoluminescence properties of the nano-carrier facilitated the visualization of drug delivery through the utilization of fluorescence microscopy[134] (Table 10).

Challenges in Nanomedicine Development

While nanomedicines show tremendous potential, several challenges must be addressed for successful clinical translation. First and foremost, achieving optimal targeting efficiency remains challenging. Nanocarriers must be engineered to

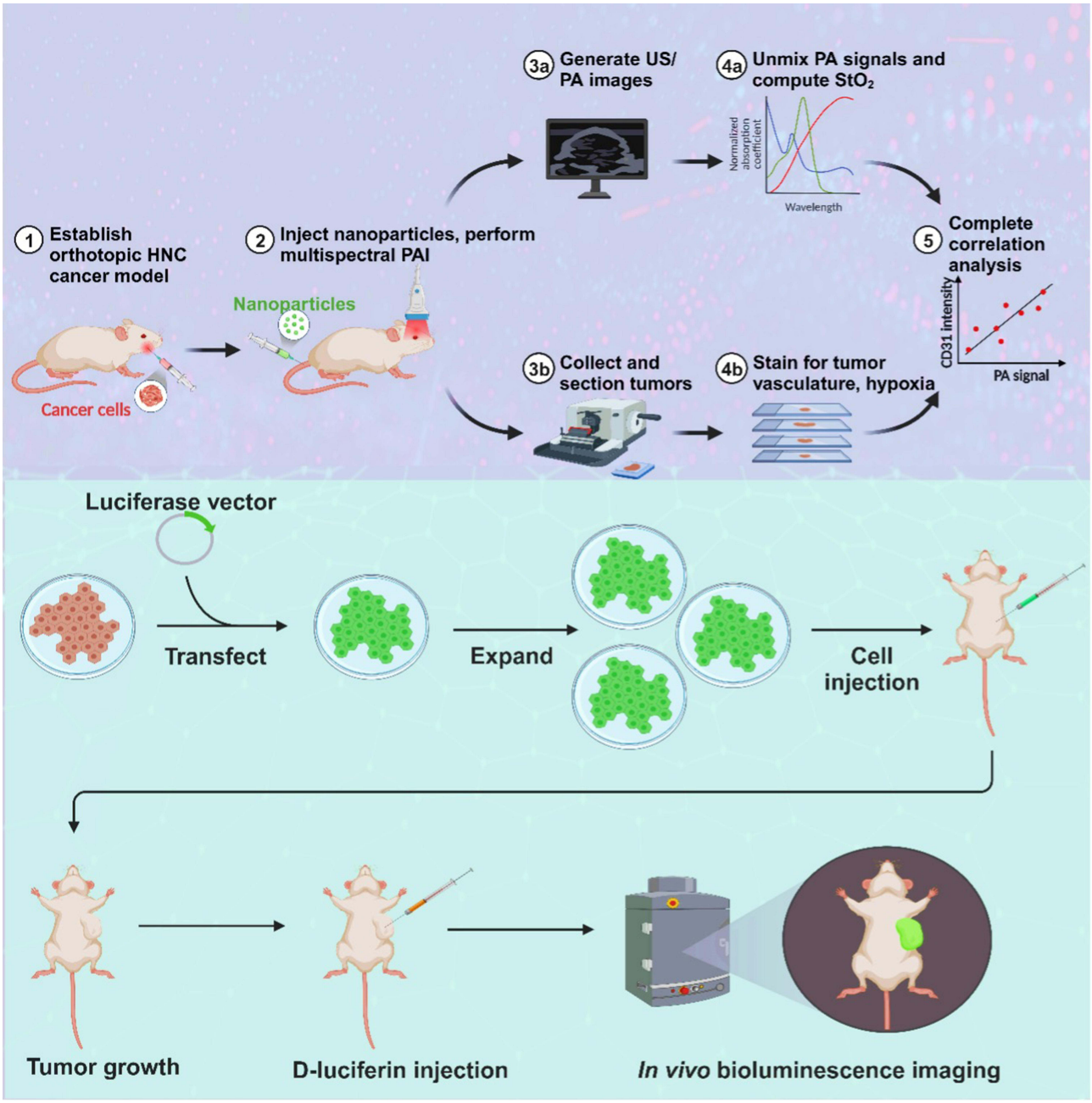

Figure 10 Integrated Methodology for Nanoparticle-Assisted Imaging and Tumor Analysis in Orthotopic Head and Neck Cancer Models (Created with BioRender.com).

Table 9 Comparison of BSA-Based Nano-DDS with Traditional Imaging Techniques.

Imaging Technique	Advantages	Limitations
BSA-Based Nano-DDS	Cost-effective, sensitive, non-invasive	None
Fluorescence Imaging	High sensitivity, real-time imaging	Photobleaching, limited penetration depth
Magnetic Resonance Imaging	Excellent soft tissue contrast, high spatial resolution	Limited sensitivity and low contrast for small lesions
Two-Photon Excitation	Deep tissue penetration, reduced phototoxicity	High-cost equipment and lower efficiency

Note: Data from.[133,134]

Table 10 Biopolymer-Based Nanocarrier Targeting Tumor/Cancer Cell Lines.

Nanocarrier	Drug moieties	Cancer Cell
Propyl starch	Docetaxel	Colon cancer
Amine functionalized polyacrylamide	Photosensitized drug (Photofrin-conjugated)	Breast Cancer
RGD peptide (Arginine-Glycine-Aspartic Acid)- conjugated triblock polymer	Camptothecin	Brain cancer/glioma
Amine-modified layered double hydroxide	NIR (Near infrared) optical contrast agent, Indocyanine green	Colon cancer
Chitosan	Quantum Dots	Non-Hodgkin lymphoma cancer cells
PEG-functionalized Melanin nanoparticles	Image contrast agents	Hepatocellular carcinoma

Note: Data from Wang C, Tao H, Cheng L, Liu Z. Near-infrared light induced in vivo photodynamic therapy of cancer based on upconversion nanoparticles. Biomaterials. 2011;32(26):6145–6154.134.[134]

selectively deliver drugs to tumor sites, maximizing treatment efficacy while minimizing damage to healthy tissues. Additionally, ensuring the stability of nanomedicines during circulation and controlled drug release at the target site is crucial for therapeutic success. Moreover, biocompatibility and safety assessments are essential to mitigate potential toxicities associated with nanocarrier materials. These challenges demand rigorous preclinical evaluations and thorough testing before moving to clinical trials. As nanomedicines advance toward clinical applications, scalability and cost-effective manufacturing become critical considerations. The ability to produce nanomedicines in bulk while maintaining reproducibility is essential for widespread clinical use. Advances in manufacturing processes and regulatory compliance are essential to ensure the quality, safety, and efficacy of nanomedicine formulations. Despite the challenges, the outlook for nanomedicines in cancer therapy is highly optimistic. Innovative materials, such as charge-convertible polymers, melanin, and gold nanoclusters, offer favorable prospects for multifunctional theragnostic applications. The integration of PDT and persistent luminescence materials holds great promise in enabling non-invasive and targeted treatment modalities with fewer side effects. Nanomedicines can revolutionize cancer therapy by improving drug delivery efficiency, overcoming drug resistance, and offering personalized treatment options.

To fully realize the potential of nanomedicines in cancer therapy, collaborative efforts between researchers, clinicians, and pharmaceutical industries are crucial. Close cooperation between these stakeholders will accelerate the development and implementation of nanomedicine-based therapies. Robust translational research and clinical trials are imperative to validate the safety and efficacy of nanomedicines, leading to their eventual adoption in clinical practice. This paper provides valuable insights into the cutting-edge research and prospects of nanomedicines in cancer therapy. By addressing challenges related to nanocarrier design, manufacturing, and safety, nanomedicines offer a promising avenue for revolutionizing cancer treatment. With ongoing research and collaborative efforts, nanomedicines may usher in a new era of targeted and personalized cancer therapies, providing hope for improved treatment outcomes and better quality of life for cancer patients.

Future Prospects

Prospects in nanomedicine for cancer therapy are promising, with several innovative approaches on the horizon. One such avenue is exosome-mediated drug delivery, which involves utilizing exosomes as natural nanocarriers to transport therapeutic payloads to specific target cells. Exosomes have shown great potential for targeted drug delivery, as they can be engineered to carry various cargoes, including drugs, siRNAs, and proteins, and possess the ability to bypass biological barriers and efficiently deliver their cargo to tumor cells. Additionally, exosomes have inherent biocompatibility and low immunogenicity, making them favorable candidates for clinical applications. Another promising development is the use of proteolysis-targeting chimeras (PROTACs) in cancer therapy.[135] PROTACs are small molecules designed to degrade disease-causing proteins by recruiting ubiquitin ligases to the target protein, leading to proteasomal degradation. This novel approach offers several advantages, including improved selectivity and reduced off-target effects compared to traditional small-molecule inhibitors.[135] PROTACs have shown potential in targeting difficult-to-drug proteins, including those involved in drug resistance and undruggable oncogenic targets. Incorporating PROTACs into nanocarriers could further enhance their efficacy and target specificity, leading to more effective and personalized cancer therapies. In conclusion, the future of nanomedicine in cancer therapy is promising, with exosome-mediated drug delivery and PROTACs playing pivotal roles in revolutionizing cancer treatment approaches.[135,136] As researchers continue to explore and harness the full potential of nanomedicine, we can look forward to safer, more effective, and personalized cancer therapies that bring us closer to the goal of eradicating cancer and improving the lives of millions of patients worldwide.

Conclusion

Nanomedicine has shown considerable promise in revolutionizing cancer therapy by leveraging the unique properties of nanoparticles to enhance drug delivery and treatment efficacy. However, despite the exciting advancements demonstrated in preclinical animal models, the translation of these innovations into clinical success remains a significant challenge. The discrepancy between preclinical and clinical outcomes highlights the urgent need for a deeper understanding of the dynamics of nanoparticle behavior, particularly the enhanced permeability and retention effect, within the human body. To bridge this gap between laboratory research and patient care, it is imperative that future studies focus on the development of more sophisticated drug delivery systems (DDS) that can accurately target tumor sites while minimizing adverse effects. This involves not only the creation of novel nanomedicines but also the refinement of existing ones to improve their delivery characteristics and efficacy in real-world clinical settings. A thorough evaluation of these nanomedicines in clinically relevant models, which closely replicate human physiology and tumor pathology, is essential to ensure their safety and effectiveness in treating cancer. Furthermore, employing alternative research methods, such as advanced three-dimensional cancer models, can offer better insights into the clinical performance of nanomedicines, thereby reducing the translational gap. These models can provide a more accurate representation of human tumors, facilitating the development of nanomedicines that are more likely to succeed in clinical trials. In addition to scientific and technical advancements, successful translation of nanomedicines into clinical practice requires a concerted effort from researchers, clinicians, regulatory bodies, and patients. Interdisciplinary collaborations are crucial in navigating the complex landscape of nanomedicine development, from formulation and testing to regulatory approval and clinical application.

In conclusion, while the journey from bench to bedside is fraught with challenges, the potential of nanomedicine in transforming cancer therapy remains immense. By addressing current limitations and harnessing the collaborative power of the scientific community, we can make significant strides toward realizing the full potential of nanomedicines. This concerted effort will not only advance the field of nanomedicine but also significantly improve cancer treatment outcomes, offering hope to patients worldwide and marking a new era in personalized and effective cancer therapy.

Disclosure

The author reports no conflicts of interest in this work.

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