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Nanomaterials unveiled: from atomic design to global solutions

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ABSTRACT

Stimuli-responsive drug delivery systems designed for the management of chronic disorders must exhibit critical characteristics, including the ability to evade premature systemic clearance, efficient internalization of therapeutic agents within targeted cells, and controlled release of drug molecules in response to specific physiological stimuli. Addressing the full complexity of these systems is challenging; however, a strong foundation can be established by outlining the fundamental principles governing their design and function. This exploration systematically enumerates the major classes of nanomaterials lipid-based, polymeric, inorganic, and advanced hybrid/smart platforms alongside their preparation methodologies and demonstrated applicability in biosciences. Furthermore, it highlights recent advances in nanomaterial engineering and stimuli-responsive strategies that have significantly enhanced drug targeting and development, enabling researchers to overcome longstanding knowledge barriers and expand the scope of therapeutic investigations. By integrating these insights, the discussion positions itself as a comprehensive toolbox for interdisciplinary research. It underscores the versatility of multifunctional nanocarriers across diverse biomedical and allied fields, ranging from precision drug delivery and molecular diagnostics to theranostic applications. Ultimately, the significance of these platforms lies in their potential to bridge fundamental nanoscience with translational medicine, encouraging investigators from multiple domains to harness the unique capabilities of nanomaterials for next-generation therapeutic and diagnostic innovations.

Keywords: Nanomaterials; nanocarriers; nano architectures; stimuli responsive; drug delivery.

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INTRODUCTION

Despite remarkable advances in diagnosis and treatment that have lowered mortality rates in many developed nations, chronic diseases remain the second leading cause of death worldwide, accounting for approximately one in every six deaths. Over the last decade nanotechnology is flourishing extensively and the research in various allied fields is directly or indirectly connected to nanotechnology. The nanotechnology can be stated as the developing, synthesizing, characterization and application of materials by tailoring their architecture at nanoscale [19]. The miscellaneous investigations reported that the nanomaterial can provide solutions to numerous challenges in biomedical and health care sector. The term nanoparticle usually represents minute particles of matter ranging from 1-100nm in diameter while the bulk particles up to 500nm. The nanomaterials having the diameter less than 100nm are synthesized from either a single or combination of materials [20]. Molecular nanotechnology is rapidly evolving and aligns miscellaneous concepts from molecular chemistry and physics. It focuses on the development of nanoscale architectures and products with meticulously fabricated characteristics. However, the exclusive adoption of nanotechnology and exposure to nanoparticles by the human beings, the potential challenges with respect to health and environment are also increasing significantly. To address these, multiple interesting disciples in nanoscience such as nanomedicine and nanotoxicology have emerged. The nanotoxicology

address the risks associated with the nanoparticles in external and biological environment. Whereas, the nanomedicine is focused on the exaggerating the challenges associated with nanomaterials in medical applications, bioimaging, medical diagnostics, and tissue engineering. At present, nanotechnology is emerging rapidly and provides modern synthetic and characterization tools for producing nanomaterials with controlled dimensionalities [21]. The distinctive properties of nanomaterials have catalyzed transformative advances across multiple fields. In electronics, they have driven the miniaturization of devices while enabling the creation of high-performance sensors and next-generation memory storage systems. Despite significant progress, nanomaterials remain a complex and rapidly evolving field. Researchers continue to explore and refine their synthesis, stability, toxicity, and long-term behavior. Overcoming these challenges is essential to ensure the safe, sustainable, and economically viable integration of nanotechnology across industries [22]. This perspective highlights the advancement of nanomedicine in addressing critical challenges within healthcare. By tackling complex disease mechanisms that often limit conventional therapies, nanomedicine offers more effective solutions. Targeted delivery systems enhance therapeutic efficacy while reducing side effects. Personalized medicine is rapidly advancing, with treatments increasingly tailored to individual patient needs. The development of nanomaterials with enhanced drug solubility, stability, and biodistribution is vital to ensure greater concentrations reach the intended site of action. Therefore, the demands are fulfilled with the development of multifunctional nanomaterials that fulfill the current demands [23]. Although numerous techniques exist to control crystallinity and morphological attributes, their sustainability and scalability for large-scale production remain constrained. This critical review delivers advanced insights into synthetic strategies and mechanistic approaches for stabilization, while also identifying key technical gaps. Addressing these limitations is essential to charting viable directions for sustainable nanotechnology [24].

Lipid based Nanomaterials

Solid lipid nanomaterials (SLN): The lipid-based nanotechnology has been widely used for encapsulation and delivery of a variety of drug molecules in various models including nanosuspensions, Nano emulsions, nanoliposomes, and solid lipid nano carriers and nano lipid carrier systems. They are widely preferred for the encapsulation and delivery of a numerous carriers such as liposomes, emulsions, and polymeric nanoparticles because of their ease of manufacture, economical, stability, enable to form dispersion systems, and enhanced entrapment efficacy. The limitations in the conventional lipid carrier systems such as lack of industrial scalability, decreased entrapment efficacy, and complications in production has led to the emergence of SLNs. The SNLs were exposed in 1991 and fond much better than then colloidal systems. They are generally spherical in shape with the diameter ranged from 50 to 1000nm. The SLNs consist of a high melting point lipid core and terminally coated with a liquid surfactant. The concentration of the liquid surfactant is optimized between 0.5-5% that enables the easy dispersion of nanoparticles and stabilized them accordingly. The SLNs have revealed a new dimension in drug delivery as it combines the characteristics of nano emulsions, liposomes and nanoparticles. The SNLS can be surface engineered to enhance their physiochemical properties, stability, enhanced pharmacokinetic attributes, inclusion complexes, and for targeted drug delivery [2]. The nanoparticles shall be surface modified with suitable agents such as polyethylene glycol to prevent them from undergoing phagocytic and Reticular Endothelium System (RES) uptake and enhance their bioavailability. The SLNs are comprised of lipids, surfactants/ emulsifiers along with active pharmaceutical ingredients, plasmids, genes, proteins, DNA and an aqueous or non-aqueous solvent [1]. The SLNs are comprised of phospholipids which serves as the critical component for the encapsulation of active ingredients because of its exclusive properties such as biocompatibility, amphiphilic nature, and multi functionality. The solid lipids used in the preparation of SLNs can be from partial glycerides, free fatty acids, steroids, glycerides, and waxes. These undergo phase transition from liquid to solid which produces a sustained and controlled drug delivery. In addition to benefits in release kinetics, the also offer stability to the dosage form from various external factors such as temperature, light, moisture and oxygen [6]. However, in the emulsifying phase the liquid type surfactant can acta as a stabilizer and produces either water in oil or double emulsions. Several organic salts, nonionic polymers, and surfactants are used as the emulsifying agents. The optimization of surfactant ad lipid concentration is critical for generating the nanoparticles with desired size, crystallinity, stability, bioavailability, sustain or controlled release characteristics, and pharmacokinetics properties [3-5].

Nanostructured lipid carriers (NLC): The nano structures lipid carriers are considered as second-generation lipid based nano carrier systems that are explored to overcome the limitations existing with the first generation nano lipid carrier systems including drug loading, stability, and drug expulsion upon storage [7]. These are the advanced nano carrier systems that comprise of a mixture of liquid and solid lipid carriers and elicit various advantages over nano emulsions and SLNs. The presence of both solid and liquid lipid carriers results in the crystalline imperfections that enhances the entrapment efficacy

of the drug molecules. at the same time, the amorphous nature of NLCs also prevent them from explosion upon storage [8]. They offer numerous advantages in transdermal drug delivery because if their optimized size, decreased irritation and toxicity, biocompatibility, biodegradability and enhanced penetration trough the lipoidal barriers of the skin. The NLCs can be surface modified to enhance the penetration, stability and incorporated with both hydrophilic and lipophilic moieties which makes them more advantageous in the nano drug delivery. The NLCs are classified into three types such as imperfect crystal model, multiple oil in solid lipid model, and amorphous model. Type I NLCs contain liquid lipids that create crystal imperfections, enhancing drug entrapment and preventing drug expulsion. Type II NLCs incorporate a high proportion of liquid lipids, forming multiple nano compartments that improve drug loading, stability, and controlled release. Type III NLCs employ non-crystallizing lipids to form a solid amorphous matrix, enhancing stability and drug encapsulation, and are particularly suitable for lipophilic drugs and lipid–drug conjugates [9-11]. The NLCs are comprised of solid lipids obtained from steroids, fatty acids, triglycerides, waxes, partial glycerides, and liquid lipids including medium chain trigyerides, linolenic acids, oleic acid etc., and the natural oils comprising limonene, citral, and linalool etc., and surfactants such as tween 20, tween 80, poloxamer 188, cremophor EL etc. that enables the membrane fluidization and enhances the drug penetration. However, all the components in the formulation should be optimized to produce the small size particles, enhanced stability and functional characteristics [12]. The NLCs are undergo biodegradation into non-toxic bio products and cleared from the body through renal and hepatic metabolism. The surface charge, small size, and surface modifications allow them to undergo cellular internalization and produce the required therapeutic effect. But their biological safety, and efficacy are still under investigation [13].

Lipid polymer hybrids (LPH): The LPH are portrayed as the future of the nanomedicine due to their mechanical strength and sustained drug release profile of polymeric nanocores and enhanced drug loading capacity of the lipid shells. The lipid polymer hybrid nanoparticles are exclusively preferred in the nanoscience because of their structural stability and dual phase encapsulation of the nanoparticles. However, the comparative investigations of lipid polymer hybrid nanoparticles reveal that lipid-inorganic nanoparticles and silica-lipid nanocomposites provide high imaging potentialities and photo thermal effect. These nanohybrids can combine effectively small molecules, peptides, and nucleic acids, that can effectively cross the blood brain barrier and preferred in brain targeting. Despite of its advantages these nanohybrids possess certain limitations such as batch to batch variation, instability as a result of significant polymer and lipid interactions, and complexity in fabrication. Hence, these drawbacks decline their large-scale production, long term storage, and quality control. Therefore, the stringent manufacturing requires optimization of various critical parameters to produce a dosage form with pre-determined quality characteristics [14]. The term “hybrid” reflects their potentiality in incorporating polymeric and lipid particles. The lipid encourages the membrane permeability and drug loading capacity while the polymeric membrane restricts drug release. Their exclusive potentiality in enhancing the physical stability and bioavailability have encouraged their usage in the situations with inadequate drug delivery. The integration of polymeric frameworks with lipid characteristics, the nanohybrids exhibits both structural robustness and biomimetics functionalities that enhances the encapsulation efficacy enabling the controlled drug release. Therefore, these polymeric frameworks are quite useful in encapsulating both hydrophilic and hydrophobic molecules that offer a promising platform in drug delivery, theranostics, and imaging [15-18].

Polymeric Nanomaterials

Polymeric nanoparticles: Colloidal nanoparticles, typically ranging from 1–1000 nm, represent a versatile class of drug delivery systems designed for targeted therapy and controlled release. Within this category, polymeric nanoparticles are distinguished into two principal types: nanocapsules, which consist of an oily core surrounded by a protective polymeric shell, and nanospheres, which are solid matrix systems where the active pharmaceutical ingredient is either uniformly dispersed throughout the polymer or adsorbed onto the particle surface. Several well-established methods are employed for their synthesis, including solvent evaporation, where an emulsion is formed and the organic solvent is removed to yield nanospheres; emulsification/solvent diffusion, in which a partially water-miscible solvent diffuses into the aqueous phase to form particles; reverse salting-out, which uses a selective agent to separate the hydrophilic solvent from the aqueous solution; and nanoprecipitation, also known as solvent displacement, where the polymer precipitates rapidly as the organic solvent diffuses into the miscible aqueous phase, resulting in nanoparticle formation. Once produced, these nanoparticles undergo rigorous physicochemical characterization using techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to assess morphology, dynamic light scattering (DLS) to determine particle size distribution, and zeta potential analysis to evaluate surface charge and predict colloidal stability. To ensure safety and clinical applicability, biocompatibility and biodegradability are achieved by formulating nanoparticles with FDA-approved

polymers such as poly (lactic-co-glycolic acid) (PLGA), poly (lactic acid) (PLA), and poly (glycolic acid) (PGA), as well as natural polymers like chitosan, which exhibit reduced toxicity and are metabolized through physiological pathways. Despite their promise in pharmaceutical applications, polymeric nanoparticles require extensive nanoecotoxicological studies, as their long-term toxicological effects and potential environmental risks must be thoroughly evaluated to ensure safe translation from laboratory research to clinical and industrial use.

Dendrimers: dendrimers are a unique class of hyperbranched, monodisperse macromolecules with a well-defined architecture consisting of a central core, interior branches, and peripheral end-groups. Unlike typical chainlike polymers, these stand apart by matching both small-molecule precision and large-molecule form. Starting from the middle and moving outwards is one way they are made; this path grows layer after layer from the heart. Another route builds outside pieces first, then links them together at a later stage toward the center. Exactness in design comes through either approach, allowing tailored surfaces with consistent shapes. Their makeup sits between single compounds and bulky materials, giving tight hold on traits like size or reactivity. Structure repeats neatly, thanks to step-by-step assembly, making each unit nearly identical. Functionality shifts easily because ends can be swapped without changing the base layout. Precision here does not come from chance but from how layers add in an ordered fashion. What forms is neither fully molecule nor classic plastic, yet shares features with both worlds. Branching happens in set patterns, avoiding random tangles common in ordinary polymers. Surface spots respond well to modifications, while the inside stays predictable. Growth direction defines which method scientists pick, depending on desired outcome. Uniformity shows up clearly when comparing individual units under close study. Each version carries its own arrangement logic, shaped by construction sequence. Despite their small size, dendrimers pack a range of useful traits - like balanced charge behavior, natural structural organization, and strong electrical forces - that help them stay steady in biological settings. While staying water-friendly and non-toxic, they build themselves into shapes that suit medical needs well. Because they break down slowly in the body, these structures extend how long drugs remain active, reach specific tissues more easily, yet often gather in tumors thanks to leaky blood vessels near cancer sites. Once inside, linked medicines gradually separate due to internal conditions, especially when bonds respond to acidity or enzymes. Instead of floating freely, certain treatments ride on dendrimer frames, whether for genes, anti-cancer compounds, or visibility tools during scans. Beyond carrying therapies through skin layers, some types specialize in wrapping genetic material tightly, helping it enter cells precisely where needed most. Among these, PAMAM versions appear frequently in studies focused on safe gene transfer and site-specific effects. Dendrimer-metal complexes work well as contrast tools in MRI scans; at the same time, these structures boost how easily some medicines mix with water because of their many surface sites. From another angle, they act like precise detectors thanks to having multiple attachment points across their outer layer. In different settings, scientists have tested them for light-driven treatments, cleaning dirty water, skincare formulas, studying misfolded proteins, even healing burns. Their tight shape packed with active parts makes them useful carriers in medicine, imaging, and new therapies - this is what researchers found after looking closely. Even though making them takes many steps and scaling up isn't simple yet, fresh studies keep uncovering more ways to apply them in tiny-scale tech and health fields. One thing stands out clearly: progress here moves fast, driven by features you do not see often in other materials built at such small sizes.

Stimuli responsive polymers: Stimuli responsive materials change their shape, texture or behavior in response to external influences such as heat, light or acidity. These changes occur due to the fine structures within them responding to changes in the environment, e.g. electric pulses or body chemistry. The difference is that they can switch between forms at will such as opening up to allow molecules to escape when a particular condition is reached. There are those that swell or shrink in response to temperature changes; those that change in charge or dissolve differently as the pH changes. Light sensitive versions only twist, fade or become porous when they are lit. Field-guided through magnetic blends, magnetic blends move or stiffen without being touched. They are put to very useful medical purposes, particularly in directing drugs to their destinations where most needed - not moved by chance, but by characteristics which are localized in diseased districts, such as acidic foci about tumors. This accuracy helps to save healthy tissue in the process of treatment. Smart carriers responding to signals, gels that absorb water, small branched molecules, and water-soaked gels make it simpler to trap biological molecules, stay longer in the bloodstreams, and increase the detection signals to identify the diseases at an earlier time. As they are not used in medicine, these materials assist in the creation of surfaces that heal themselves, clothes that adapt to the environment, filters that purify the dirty water, and even buildings that store power more effectively. There are still issues with how to make them in large batches and to demonstrate that they remain safe within bodies over time, as well as to obtain the same reaction when used in messy real-world situations. Researchers are focused in developing novel materials that respond to multiple stimuli, through a combination of carbon based and

non-carbon-based components in order to enhance the strength and precision. Collectively, responsive matter redefines the process of creating things - moving whole sectors, such as health technology, eco-friendly design, and premium-grade machinery, with the help of adaptable, precisely sensitive operation.

Inorganic nanomaterials

Graphene, Carbon nanotubes: These architectures are designed to deliver the medicament directly to the targeted sites thereby minimizing the side effects and toxic reactions. Their base structure is made up of carbon rich small materials. One of them is unique: flat sheets of uncovered carbon, as paper thin - that is Graphene. Its surface is strongly impervious to water. However, strength, elasticity and conductivity characterize its performance under pressure. There are modified structures, Reduced Graphene Oxide (rGO) that enhances the aqueous solubility and drug loading of diverse drug molecules. During production, oxygen containing groups such as carboxyl or hydroxyl groups are manifested over the surface. Due to such additions, it becomes easier to mix with water. Attaching of drugs is not problematic. The other form is formed as well tiny specks less than ten nanometers in width referred to as GQDs. Zero dimensional almost point-like scale. Light does not easily degrade them, they are strong when they are radiant within tissue. Living systems are likely to tolerate them without much opposition. Small enough to pass through the gatekeeper of the brain, they access places that other people cannot. Carbon tubes are rolled in sheets either single or multi-layered. A lot of effort is directed at steering them in the direction required. They move to their locations without any assistance, as they are attracted by leaky segments around critical areas. In addition, they are guided by the implication of molecules such as folic acid, hyaluronan, biotin. Antibodies are homing devices that are attached to their shell. Plastic-like chains coating them conceal them to body defenses. Beginning with smart materials that wake up on conditioning - such as the unpleasant conditions of the interior of a tumor or external conditions such as the rays of heat or the invisible magnetic inducements - the article follows the way drugs can be released precisely where they are needed. Some of these materials are not very far away and can be used in two functions: to identify illness by scanning the body in finer detail and at the same time provide treatment, like targeting cells to the extent of destroying them. Although these tools may be a huge boost in the fight against cancer or intractable infections, they suffer with regulatory issues and extensive research is required to establish the safety and toxicopharmacology studies. Unrefined versions of carbon substances can damage genetic code or provoke inner upheavals. Nevertheless, refining their surface is the way to get the tension out of the situation, and the thing that was dangerous to do becomes something that is worth paying attention to going forward.

Graphene Quantum dots: These are the carbon-based nanomaterials that combine the properties of graphene and exhibit exclusive outcomes due to edge and quantum limit effects. Graphene quantum dots, also known as GQDs, are a new form of quasi-zero-dimensional carbon nanomaterials that have received overwhelming scientific attention as a result of their exceptional combination of graphene and quantum limit characteristics. Physically they are made up of single or multiple layers of small pieces of graphene that still possess the typical periodic six membered ring crystal structure of their mother material. Their size is one of the distinguishing characteristics that distinguish them among bulk graphene, which has a zero-band gap and therefore is non-luminescent. In addition to their optical brilliance, they are also well appreciated due to their high-water solubility which is explained by the availability of oxygen-containing functional groups such as hydroxyl and carboxyl groups on their surface and edges. They are also characterized by an extraordinary photostability and low biological toxicity and thus are much more environmentally and biologically friendly compared to conventional semiconductor quantum dots. The manufacturing of these materials is usually separated into the top-down and bottom-up strategies, and each of them has different benefits. The top-down method entails physical or chemical dissection of bigger source of carbon as graphene oxide, carbon nanotubes or carbon fibers. The sophisticated techniques preferred for the preparation of nanoparticles such as electrochemical peeling, solvothermal synthesis, and microwave assisted stripping produces high yield with non-uniform particle size. On the other hand, bottom-up strategies entail the assembly of the dots by small molecule building block such as glucose or citric acid based on controlled chemical reactions. Other methods like pyrolysis carbonization, C_{60} open-cage technique and chemical vapor deposition can offer better control over the final structure and size, but tend to be more complex procedures and lower-yielding of materials. Their performance is enhanced through heteroatom doping such as nitrogen, Sulphur, or phosphorous that enhances the product yield and electronic configuration of the substances. On the surface functionalization and formation of composites with other semiconductors are also typical methods of improving their photocatalytic activity by enhancing the rate of electron transfer and inhibiting the recombination of electron-hole pairs. These improvements have preconditioned extensive applications in such areas as sensing and biomedicine. They find application in the sensing industry in the creation of ammonia and nitrogen dioxide gas sensors of high sensitivity, optical sensors of metal ions and individual gene sequences. They have high biocompatibility which makes them the best choice to be used in biological imaging where

they can be used as stable fluorophores in cell labelling and tracking. Moreover, they find use in photodynamic and photothermal therapy and sophisticated drug delivery systems, which are capable of high precision and minimal side effects in tumor localization during cancer therapy. Although there are still issues with the efficiency of synthesizing and the complete comprehension of the luminescence processes, graphene quantum dots are about to become the game changers in the technological and medical developments in the future.

Advanced Hybrid and Smart Nanomaterials

Organic-Inorganic hybrids: These are a new type of material which has synergistic and complementary interactions between organic and inorganic components and exhibit miscellaneous applications in a variety of scientific fields. The key to this area is the stringent study of structural-property relations such that materials can be engineered at the molecular scale to obtain certain electronic, optical or mechanical properties. The most suitable architecture to be used in these studies is metal-organic frameworks (MOFs), especially zirconium-based systems like MOR-1 and MOR-2. The structures employ certain organic linkers such as 2-amino-terephthalic acid to form selective pore environments exhibiting high selectivity and kinetics in the purification of pharmaceutical contaminant of aqueous systems. In addition to environmental clean-up, zirconium-based structures are developing carbon dioxide capture technology and acting as scaffolds of atomically precise single-site catalysis. Similar studies in organic-inorganic copper halides have brought out so-called all-in-one structures where both ionic and coordinate bonds are present in a single molecular cluster, which has demonstrated very high structural stability and dispersibility. These low-dimensional halides are photoluminescent in the green to red spectrum with complex triplet cluster-centered excited states and charge transfer processes involving both the halides and the ligands, which are referred to as halide-to-ligand charge transfer (XLCT) and metal-to-ligand charge transfer (MLCT). These properties make these materials a good candidate as rare-earth-element-free phosphors and hypotoxicity photodetectors. Moreover, the halide perovskites field is still developing and is aimed at the optimization of the optoelectronic performance based on the interface engineering. In the recent past, there have been a one-step passivation method of two-dimensional perovskite solar cells based on [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) as an antisolvent, which is effective at reducing interfacial defects and increasing power conversion efficiency. Although two-step fabrication routes, including spin-coating, immersion, and evaporation, have potentially good prospects of commercial scalability, investigators still need to solve the stoichiometric control issues, as well as uneven precursor distributions, such as that of lead iodide. These hybrids are kept at the forefront of the current materials science through the continued optimization of crystallization kinetics by solvent and additive engineering, as well as, the use of advanced computational modeling.

Surface Engineered Nanomaterials: Nanomedicine is a fast-paced area of research in the medical field that is mainly concerned with the establishment and use of nanomaterials in prevention, diagnosis and treatment of complicated diseases. With a wide variety of structures (nanoparticles, nanotubes, nanoplates, nanowires) these materials, with their unique physicochemical characteristics, are invaluable in biomedical applications in such areas as biological imaging, biomolecular sensing, and targeted drug delivery. Nevertheless, nanomaterials to be effectively used in a clinical context have certain requirements, such as being highly biocompatible, not toxic, and able to remain in a colloidal state under physiological conditions at a broad pH range. Surface engineering is the key to the realization of such requirements enabling researchers to tune the interface of nanomaterials with polymers, natural biomolecules, or synthetic small ligands. These functionalization strategies can be broadly divided into three types replacement strategies, including ligand exchange, weak physical forces such as Van der Waals forces, hydrogen bonding, and pi-stacking, and covalent conjugation, which includes chemical linkers attaching discrete units to the surface. Polymeric coatings, such as polyethylene glycol (PEG), chitosan, and poly (lactic-co-glycolic acid) (PLGA), are commonly employed to offer steric stabilization, lessen adsorption of blood serum proteins and extend the circulation time of nanoparticles in the blood. Natural biomolecules, such as proteins, peptides, antibodies, and aptamers, are also used as targeting agents to guide nanomaterials to receptors that are overexpressed on cancer cells and promote receptor-mediated endocytosis and enhanced therapeutic efficacy. Functionalized nanomaterials are used in the delivery of advanced cancer treatment methods, including magnetic hyperthermia, in which iron oxide nanoparticles produce heat under an alternating magnetic field to cause tumour necrosis, and photodynamic therapy, in which photo switchable photo sensitisers use light to generate cytotoxic oxygen species. Besides cancer, the materials have an important role in tissue engineering as nanoscaffolds that recapitulate the mechanical and biological properties of the native extracellular matrix to support cell adhesion, cell proliferation, and cell regeneration in bone and cartilage. Additionally, medical implants e.g. cardiovascular and orthopaedic implants are surface-engineered to enhance their mechanical characteristics, compatibility with bone, and antimicrobial properties against pathogens. Although these engineered nanostructures have

enormous potential, toxicity of nanomaterials is a major issue and the levels of toxicity are greatly determined by the particle size, especially those less than 50 nanometres, shape, composition, and crystalline structure. Developing studies also point to the cost-efficient functionalisation strategies, including the application of mixed DNA and PEG monolayers, to make sure that these advanced nanotechnologies can be expanded effectively in large scale to be used in industry and medicine on a large scale.

Multifunctional systems (theranostics): Theranostic nanoparticles are a complex system that is designed to allow personalization of disease control that provides real time information of biochemistry and morphology of a tumor and at the same time delivers pharmacological cargoes at scale and time. In the nanomedicine field, the ideal theranostic agents have some disadvantages including rapid and site-specific accumulation, stimulus responsive drugs release and biocompatible degradation to nontoxic metabolites. The initial designs had taken advantage of the Enhanced Permeability and Retention (EPR) effect which is a passive process relying on leaky tumor vasculature. Nevertheless, it is not as reliable as it is heterogeneous due to the variability in the microenvironment of tumors and fluctuating extravasation kinetics. This has caused a shift in research where active targeting techniques are used like surface-conjugated ligands like antibodies, aptamers and peptides to specifically target overexpressed receptors on malignant cells or tumor associated endothelium. Some of the fabrication methods include polymeric encapsulation, mesoporous silica structures and inherently theranostic structures (porphysomes and gold nanoshells). Although a few systems such as the iron oxide nanoparticles (IONPs) and others made of gold nanostructures have progressed into clinical trials, with the majority of theranostic systems still in preclinical stage. The nanothanostics frontier involves the focus on the so-called smart functions, including prodrugs controlled by intracellular signals (e.g., pH gradient, thiol concentration), which allows tracking the drug release in real time. There is growing interest in new principles such as cooperative targeting, in which low doses of nanoparticles are used to adjust tumor vasculature, and thus, improve the subsequent accumulation of nanoparticles. However, synthetic reproducibility, efficiency of conjugation of ligands and long-term toxicity of inorganic elements should be solved to realize clinical translation of these potent technologies.

CONCLUSION

Nanomaterials have become a key element of contemporary science, providing unprecedented prospects to structure and control matter on nanoscale to a variety of applications. Self-assembled, solvent evaporated and microfluidized methods are all used to produce lipid-based nanomaterials that are highly biocompatible and able to deliver drugs to specific targets. Polymeric nanomaterials, typically prepared through emulsion polymerization, nanoprecipitation, or controlled radical methods, offer adjustable mechanical strength, biodegradability and release profiles. The inorganic nanomaterials are formed by sol-gel, hydrothermal or chemical vapor deposition pathways and provide stability, multifunctionality and special optical or catalytic characteristics. Hybrid and smart nanomaterials combine these strengths, with organic and inorganic building blocks or stimuli-responsive capabilities to enable flexibility and multimodality

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