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Bio-nanomaterials: An Introduction

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1.1 Introduction

A bio-nanomaterial encompasses a diverse array of biological molecules and components, such as proteins, antibodies, enzymes, nucleic acids, lipids, polysaccharides, oligosaccharides, viruses, and secondary metabolites, organized at the molecular level to form materials with unique properties and functions [1, 2]. Nanotechnology, a multidisciplinary domain focused on materials at the nanometer scale (1–100 nm), has experienced significant advancements in recent years [3]. This field has diverse applications that extend across a wide spectrum of scientific fields, demonstrating its extensive impact and significance. The term "nanotechnology" stems from the Greek word "nano," denoting one-billionth of a meter, coined by Norio Taniguchi in 1974. This field has significantly advanced medicine by introducing nanosized particles and materials known for their exceptional biocompatibility and minimal toxicity, offering promising avenues for medical innovation and treatment. Bio-nanomaterials are the term assigned to nanosized materials, either composed of or produced through biological means. Nanoparticles, due to their minute size, exhibit extraordinary attributes across various domains including structure, chemistry, physics, optics, heat conductivity, mechanical strength, and electrical conductivity. Their distinctive characteristics position them as versatile tools in the biomedical sector, playing crucial roles in tasks such as advancing tissue engineering, regenerative medicine techniques, drug and gene delivery systems, cancer treatment modalities, and neurodegenerative disease therapies, thereby offering innovative solutions for addressing complex medical challenges [4]. For instance, drug delivery systems are designed to release drugs on target; gene therapy uses vectors that specifically enter targeted cells; cancer treatment employs nanoparticles (NPs) that selectively destroy tumor cells selectively; neurodegenerative diseases are addressed via therapeutic strategies that target specific pathological accumulations andinflammation is managed by therapeutic

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agents that regulate host immune responses among other possible causes of illnesses [5]. Furthermore, various bio-nanomaterials are utilized as diagnostic tools for identifying various biomarkers or as imaging agents for medical examinations.

Many biodegradable polymers and naturally sourced nanomaterials have been widely employed across biomedical, pharmaceutical, industrial, packaging, and agricultural sectors for the development of bio-nanomaterials. Manipulating materials at the nanoscale now enables fundamental interactions with biological systems, paving the way for customized medication delivery. This breakthrough opens avenues for precise and efficient illness treatment while minimizing adverse effects. Furthermore, bio-nanomaterials are essential in the creation of biosensors and imaging agents, which transform diagnostic methods and make it possible to identify various medical disorders early [6]. Hence, a wide array of biodegradable polymers and naturally derived nanomaterials have found extensive applications across diverse sectors, including biomedical, pharmaceuticals, industrial packaging, and agriculture (Figure 1.1). The utilization of bio-nanomaterials can be traced back to ancient Indian literature, particularly in Ayurveda, a traditional system of medicine practiced in the Indian subcontinent since the 7th century. Ayurvedic treatments often incorporate metal ash, known as Bhasma, to address various diseases [7]. Bhasma comprises metallic or mineral preparations that are treated

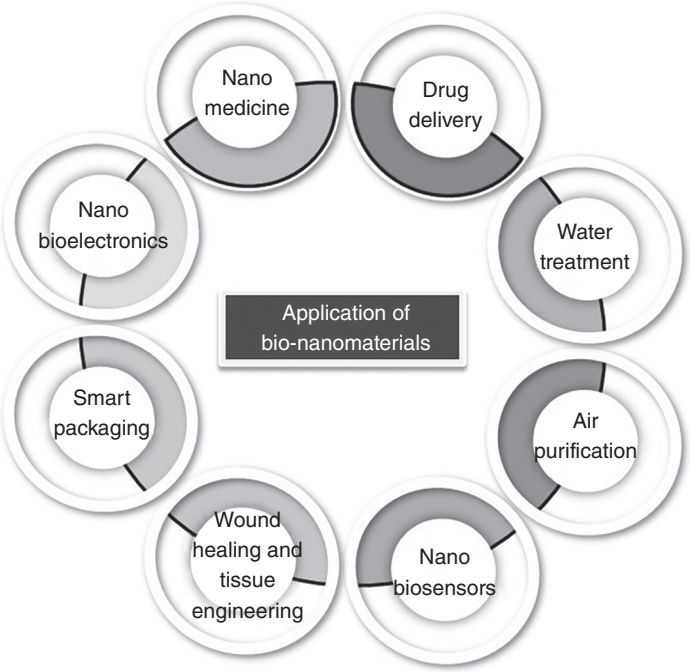

Figure 1.1 Applications of bio-nanomaterials. The figure illustrates the diverse range of applications of bio-nanomaterials across various fields, highlighting the versatility and potential impact of bio-nanomaterials, driving innovation and addressing pressing societal needs across diverse domains.

with herbal juices or decoctions and subjected to specific heating processes, as outlined in the puta system of Ayurveda. Widely recommended across India, Bhasma, a form of bio-nanomaterial, is administered either alone or in combination with medicinal plant extracts or powders, depending on the specific therapeutic needs of the patient [8]. Bio-nanomaterials exhibit diverse applications in environmental remediation, offering significant potential to address various environmental challenges. Both natural and artificial bio-nanomaterials possess unique attributes that can be harnessed to develop efficient and durable remediation methods. These materials hold promise in reducing pollution, restoring ecosystems, and promoting sustainable environmental practices.

The chapter involves the types of bio-nanomaterials, the various kinds of bio-nanomaterial conjugates, and the application of bio-nanomaterials in various fields ranging from health care and sustainable environmental technologies.

1.2 Types of Bio-nanomaterials

Bio-nanomaterials could be the derivatives of macro biomolecules (biological NPs) or they could be organic or inorganic compounds synthesized via the mediation of biological materials (derived bio-nanomaterials) (Table 1.1).

1.2.1 Classification of Biological Nanoparticles

Biological NPs are classified into four major categories derived from biomolecules or synthesized from organic building blocks, i.e. proteins, nucleic acids, lipids, and polysaccharides.

1.2.1.1 Proteins

Proteins are polymers of amino acids and can be the predecessor for the production of NPs, specifically oligopeptides composed of 8–20 amino acids. Due to their unique functionalities and the defined primary structure, these peptides are used for surface modification and attachment of various compounds that might be used for drugs and therapeutics [41, 42]. The ability of protein to form gels, emulsions, and dried particles, along with their capacity to synthesize NP with controlled size distribution, make them novel candidates for NP synthesis [43]. There are a number of proteins used for the NPs formulation: gelatin, elastin, collagen, gliadin, zein, ferritin, albumin, and silk protein (sericin and fibroin) [44–46].

By integrating principles from physics, engineering, chemistry, and biology, we have harnessed the capability to engineer biological nanomaterials at the molecular scale, utilizing self-assembling peptide systems. Peptides serve as the building blocks for creating a diverse array of nanostructures, including but not limited to nanofibers, nanotubes, vesicles, nanometer-thick surface coatings, and nanowires. Self-assembling peptides play multifaceted roles, ranging from stabilizing membrane proteins to creating favorable environments for cell growth and tissue repair in regenerative medicine. Moreover, they aid in gene and drug delivery, showcasing

Table 1.1 Overview of various strategies for biomolecule–nanoparticle integration.

S. no.	Material	Fabrication method	Particle size and characteristics	Application	References
1	Bovine serum albumin (BSA)	Dynamic aggregation, radiation-induced cross-linking	20–40 nm	Drug carrier	[9–11]
2	Cruciferin	Cold gelation	~200 nm spherical, polydispersity index (PDI) of 0.2–0.3	Delivery of bioactive food components	[12, 13]
3	Chimeric polypeptide	Genetically encoded synthesis in E. Coli	60 nm, nearly monodisperse	Treatment of cancer Conjugated drug: paclitaxel	[14–16]
4	Fibronectin	Electrospraying	28.2–31.52 nm	Functionally active protein for tissue engineering	[17–20]
5	Zein	Electrospraying	175–900 nm	Encapsulant for food coloring and ingredients	[21–25]
6	Fluorescent proteins	Liquid nanodispensing (NADIS)	50 nm–microns	Nanodevice (scanning probe lithography)	[26–28]
7	Fibroin	Electrospraying	80 nm	Wound dressing and tissue engineering	[29–31]
8	Whey protein isolate (WPI)	Homogenization-evaporation	90 nm	Delivery vehicle for beta-carotene to intestine	[26]
9	Chitosan oligosaccharide/ β-lactoglobulin	Ionic gelation	150–30 nm, spherical	Delivery of hydrophobic bioactive compounds into aqueous foods	[32–35]
10	Bioactive peptides/ chitosan	Ionic gelation	151 ± 4.3 nm, PDI = 0.05–0.14	Encapsulant of epigallocatechin-3-gallate (EGCG) for nanochemoprevention	[36, 37]
11	Chitosan	Ionic gelation	550–850 nm, spherical with some irregular shape particles	Protein carriers in tissue engineering	[38–40]

their versatility as tools for crafting sophisticated architectures, innovative materials, and nanodevices. These capabilities drive advancements in nanobiotechnology and various engineering disciplines. Positioned at the intersection of various disciplines such as chemistry, materials science, molecular biology, and engineering, molecular self-assembly harnesses nature's vast potential to advance across disciplines and enhance societal well-being. Nanofibers, elongated cylindrical structures measuring between 5 and 20 nm, possess a high surface-to-volume ratio that facilitates the incorporation of a wide array of bioactive molecules, including nucleic acids [47]. Among the peptides capable of self-assembly, examples include amyloid peptides, ionic self-complementary peptides, collagen-like triple helical peptides, and amphiphilic peptides, all of which can spontaneously organize into nanofibers [48].

1.2.1.2 Nucleic Acid

DNA and RNA possess the remarkable capability to form controlled and three-dimensional-oriented NPs. Their inherent affinity for complementary sequences allows nucleic acids to self-assemble into intricate, multidimensional structures with particular control over size and shape. This self-assembling ability results in the formation of compact and stable NPs, offering a versatile platform for various applications in nanotechnology and biomedicine [49]. The versatility and inherent characteristics of nucleic acids enable the precise engineering of single-stranded DNA or RNA molecules, resulting in the formation of modular nucleic acid nanoparticles (NANPs). These NANPs offer the flexibility to be intricately tailored into elaborate three-dimensional structures composed entirely of nucleic acids. RNA and DNA molecules assemble into diverse higher-order structures through both canonical and noncanonical base pairings, serving as the foundation for creating a range of nanostructures such as rings, fibers, and polygons [50–52]. By carefully choosing nucleic acid components, NANPs can be fine-tuned to modify their physicochemical properties, biological activities, and versatility. In the realms of biotechnology and biomedicine, NANPs emerge as promising carriers for bioactive compounds, tools for molecular imaging and biosensing, scaffolds for biochemical reactions, and multifunctional NPs amalgamating diverse functionalities within a unified structure.

The expanding domain of nucleic acid nanotechnology has brought forth a multitude of synthesis protocols tailored for NANPs, along with established classification methodologies enabling their study both in controlled laboratory environments and within living organisms. Moreover, compelling proof-of-concept data has emerged, underscoring their potential across diverse therapeutic applications [53–55].

1.2.1.3 Lipids

The fragmentation of lipids can give rise to various nanostructures, including liposomes, nanoemulsions, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs). These diverse lipid-based nanocarriers offer versatile platforms for drug delivery, enabling precise control over drug release kinetics, bioavailability, and targeting efficiency. These structures can be used for encapsulation of drugs to increase the efficiency by targeted delivery and preventing degradation of NPs [56, 57].

Liposomes, developed with an outer bilayer of amphipathic molecules like phospholipids enclosing an aqueous compartment, emerged as pharmaceutical products in the early nineties, with examples Alveofact® and Ambisome®. They possess several advantageous attributes as drug carriers: biological inertness, complete biodegradability, lack of toxicity, antigenicity, or pyrogenicity due to the natural presence of phospholipids in cell membranes. Additionally, liposomes can be tailored in terms of size, composition, and surface charge for specific applications, and they can encapsulate a wide range of hydrophilic and lipophilic drugs, offering possibilities for drug targeting. In the past two decades, SLNs, also known as lipospheres or nanospheres, have emerged as alternative particulate drug carrier systems, particularly suitable for lipophilic and poorly water-soluble drugs. With particle diameters ranging from approximately 10–1000 nm, SLNs combine the advantages of other carrier systems, including high biocompatibility, bioavailability, controlled release, physical stability, and protection of labile drugs from degradation. They are compatible with various administration routes such as oral, intravenous, pulmonary, and transdermal routes, thereby mitigating associated challenges [58].

1.2.1.4 Polysaccharides

Polysaccharides are a kind of carbohydrate polymers linked via glycosidic bonds. The most commonly used polysaccharide for NP is chitosan. Chitosan is a cationic polyaminosaccharide. Due to the presence of high-density amino groups and mucoadhesive properties, the reaction kinetics for the formation of new chemical bonds or negative complexation is very high [59]. The chitosan NPs easily conjugate with proteins, plasmid DNA, antigens, and bioflavonoids [60–62].

Polysaccharides, hydrophilic polymers derived from natural sources, are extensively employed in water-based polymer systems and nanotechnology owing to their advantageous attributes in biological settings. These include biodegradability, biocompatibility, and minimal toxicity, making them highly desirable for various applications. The exceptional properties of polysaccharides render them excellent candidates as building blocks for NP fabrication, particularly in medical therapy. The use of polysaccharides offers a plethora of benefits, such as high loading efficiencies, rapid drug release rates, precise targeting capabilities, remarkable stability, and minimal toxicity in physiological environments. Moreover, polysaccharides are abundant, easy to process, and derived from sustainable feedstocks, further enhancing their appeal. Chemical functionalization of polysaccharides, mainly via free carboxyl and hydroxyl groups, allows the creation of tailored polysaccharide derivatives with specific properties, facilitating their use in various applications. Various methodologies have been devised to synthesize polysaccharide-based NPs with precise control over size, morphology, and structure. These approaches encompass mechanisms such as ionic cross-linking, covalent cross-linking, self-assembly of hydrophobically modified polysaccharides, polyelectrolyte complexation, and the formation of polysaccharide–drug conjugates. The choice of synthetic route is crucial to optimize NP properties for specific applications, considering factors such as physicochemical

parameters of polysaccharides, polysaccharide composition, NP size, and surface morphology. It is vital to note the distinction between NPs and nanocrystals, with NPs being amorphous particles and nanocrystals being crystalline, to avoid misunderstandings in terminology. While polysaccharide nanocrystals will not be discussed in detail, some useful applications will be mentioned [63].

1.2.2 Derived Bio-nanomaterials

There are various nanosized biomaterials that can be categorized as derived bio-nanomaterials. This is further categorized as the artificially synthesized nanomaterial mediated by biological compounds and the biological component which is part of organisms.

1.2.2.1 Green Synthesized Nanoparticles

Metal NPs can be developed via various chemical, physical, and radiation techniques. These methods encompass chemical reduction, precipitation, electrochemical deposition, sol-gel processes, physical vapor deposition, laser ablation, and irradiation-induced synthesis, among others. Each approach offers distinct advantages and allows for precise control over the size, shape, and properties of the resulting NPs, catering to specific applications in fields ranging from catalysis to biomedicine. The drawback associated with these methods is the potential for toxicity due to the use of certain chemicals, high temperatures, or radiation during the synthesis process. Metal and metal oxide NPs can be synthesized through the involvement of biological elements such as plant extracts, bacterial extracts, fungal extracts, seaweed, polysaccharides, biodegradable polymers, botanical materials, and algae. The green synthesis of NPs is a single-step process, environmentally benign, simple, economically viable, and clean technology as it does not involve harsh chemicals and zero harmful by-products. The biosynthetic pathways utilized for NP fabrication present a unique advantage by enabling the simultaneous reduction and stabilization of metal NPs within a single-step synthesis process [64].

1.2.2.2 Nanosize-Derived Component

Viruses, with sizes ranging from a few nanometers to hundreds of nanometers, present an intriguing avenue for various biomedical applications. Their surfaces can be modified and targeted for therapies such as cancer treatment, immune therapy, drug delivery, and detection. To date, only one viral therapy, T-VEC (Imlygic), a modified herpes simplex virus (HSV), has received Food and Drug Administration (FDA) approval for the treatment of cancer, specifically for subsets of patients with melanoma [65]. Viral nanoparticles (VNPs) encompass a diverse range of viruses, including plant viruses, bacteriophages, and mammalian viruses. Genome-free versions of VNPs, known as virus-like particles (VLPs), find utility in gene therapies, cancer therapies, antimicrobial therapies, immunotherapies, vaccines, cardiovascular therapies, imaging, and theragnostics [66].

1.3 Integration of Nanoparticles and Biomolecules

The size of biomolecules is comparable to NPs. The size similarity gives the advantage for the physical interaction with the NPs, which might lead to many noncovalent interactions such as ionic interaction, hydrophobic interaction, and solvation effect. Biomolecules, due to their intrinsic properties of donating electron clouds or accommodating excess negative charge, covalent bond formation, and stabilizing the volatile compound, lead to the formation of biomolecule–NP hybrids, which have characteristics of both NPs and biomolecules [67]. The intrinsic features of biomolecules could be used for the building block of NP architecture (Table 1.2). The protein molecules have various binding sites that could facilitate the development of multifunctional NPs [99].

1.3.1 Different Processes of Synthesis of Nanoparticles and Biomolecules Integration

1.3.1.1 Conjugation via Noncovalent Interactions

Noncovalent conjugation strategies are physical interactions involving electrostatic, hydrophobic, and affinity forces [100]. The ionic interaction between biomolecules and NPs offers a robust and stable approach to engineering desired complexes. This process involves either imparting the desired charge to NPs for binding with targeted biomolecules or binding biomolecules with charged ligands or specific buffers to enable binding with oppositely charged NPs [101]. For instance, to incorporate siRNA effectively, lipid NPs can be modified with supercharged coiled-coil arginine-rich proteins. This modification enables the NPs to interact with negatively charged RNA molecules, facilitating the encapsulation and delivery of siRNA for targeted gene silencing applications [102]. Another example is a self-assembled nanocomplex formed by negatively charged fucoidan (a sulfated polysaccharide) and positively charged protamine [103]. The advantage of a noncovalent electrostatic complex is the synergistic combination of functional properties of both.

Hydrophobic interaction also helps in binding of peptides onto the surface of silica at various pH conditions. By tuning the surface property of NPs and binding environment, the biomolecules adsorption on NPs can be regulated [104]. Similarly, gliadin, a protein NP can interact with Resveratrol via hydrophobic interaction [105].

1.3.1.2 Conjugation via Covalent Interactions

The covalent interaction that occurs between biomolecules and NPs is called chemisorption. In chemisorption, biomolecules having a thiol group (cysteine residue) can form a link with the NPs [106]. In instances where thiol residues are absent, a thiol group can be chemically introduced onto biomolecules using Traut's reagent (2-aminothiolane). This reagent enables site-specific modification by reacting with primary amines, facilitating the attachment of thiol groups for subsequent conjugation or functionalization processes [106, 107]. Noble metal NPs, especially gold (Au), are highly reactive to the thiol group. Au can form a strong bond with sulfur (Au—S). This has been exploited in forming various conjugates of Au NPs of peptides, DNA, antibodies, and proteins [99, 100, 108].

Table 1.2 Various conjugation strategies and applications for nanoparticles conjugated with biomolecules.

S. no.	Biomolecule	Nanoparticle	Types of conjugates	Conjugation strategy	Application	References
1	Aptamers	AgNP/Fe_3O_4	Biomolecule–hybrid nanoparticle conjugates	Streptavidin-biotin affinity binding	Detection of *Staphylococcus aureus*	[68]
2	α-Amylase, pectinase, cellulose	Fe_3O_4	Organic–inorganic nanoparticle conjugates	GA cross-linking	Clarification of fruit juices	[69]
3	AntHocyanin-rich extract	Whey protein isolate/beet pectin	Organic–organic nanoparticle conjugates	Electrostatic complexation	Encapsulation of natural colorants and food nutraceuticals	[70]
4	Bovine serum albumin (BSA)	Tripolyphosphate-cross-linked chitosan	Organic–organic nanoparticle conjugates	Electrostatic interaction, encapsulation	Sustained release of protein	[60]
5		PLGA, HPMA/Ac-DAPBoc	Biomolecule–polymeric nanoparticle conjugates	Coaxial electrospraying, one-pot synthesis	Delivery of platinum drugs into cancerous cells	[71, 72]
6		Amphiphilic polymer-coated hydrophobic silver nanoparticles	Biomolecule–hybrid nanoparticle conjugates	Physisorption	To study protein-nanoparticle interaction	[73]
7		Copper(II) phosphate	Self-assembled biomolecule–nanoparticle hybrid	—	Decomposition of organic dyes in wastewater treatment	[74]
8	Beta-carotene	Whey protein concentrate	Organic–organic nanoparticle conjugates	Encapsulation	Encapsulation of bioactives	[75]
9	Chitosan	Polylactic acid/nifedipine	Biomolecule–polymeric nanoparticle conjugates	Encapsulation	Treatment of angina pectoris and hypertension	[75]
10		Bioactive glass	Organic–inorganic nanoparticle conjugates	Noncovalent	Injectable scaffolds in bone and cartilage repair	[76]

(*continued*)

Table 1.2 (Continued)

S. no.	Biomolecule	Nanoparticle	Types of conjugates	Conjugation strategy	Application	References
11	Cholesterol	Polyamidoamines	Biomolecule–polymeric nanoparticle conjugates	Covalent	Tamoxifen delivery	[77]
12	Cisplatin	PCL-block-PEGdiblock copolymer	Biomolecule–polymeric nanoparticle conjugates	Encapsulation	Treatment of glutathione over-expressed breast cancer cells	[78]
13	Curcumin	*O*-Carboxymethyl chitosan/fucoidan	Organic–organic nanoparticle conjugates	Cross-linking	Oral delivery system	[79]
14		Zein–pectin/alginate	Organic–organic nanoparticle conjugates	Electrostatic interaction, encapsulation	Functional foods and beverages	[80]
15		Albumin–polycaprolactone	Biomolecule–hybrid nanoparticle conjugates	Covalent	Drug delivery system for prostate carcinoma therapeutics	[81]
16	DNA	Magnesium phosphate	Organic–inorganic nanoparticle conjugates	Entrapment	DNA vaccine formulation	[82]
17	(−)-epigallocatechin-3-gallate	Peptide/chitosan	Organic–organic nanoparticle conjugates	Encapsulation	Nano-chemoprevention	[83]
18	Glucose oxidase	Fe_3O_4/polypyrrole	Biomolecule–hybrid nanoparticle conjugates	Encapsulation	Potentiometric glucose biosensor	[84]
19	α-Lactalbumin and lipase	Copper(II) phosphate	Self-assembled biomolecule–nanoparticle hybrid	—	Biosensors	[85]
20		Hydroxyapatite-encapsulated-c-Fe2O3	Biomolecule–hybrid nanoparticle conjugates	Encapsulation covalent	Interesterification of soybean oil	[86]
21	Lysozyme and β-lactoglobulin	Silica	Organic–inorganic nanoparticle conjugates	Electrostatic interaction	Not specifically mentioned	[87]

22	Mussel adhesive proteins	Iron(III)-3,4-dihydro-xyphenylalanine (DOPA)	Organic–inorganic nanoparticle conjugates	Cross-linking	pH-responsive drug delivery Model drug: Doxorubicin	[88]
23	Organic fluorescent dye	PVP/SiO_2/Fe_3O_4	Biomolecule–hybrid nanoparticle conjugates	Encapsulation Electrostatic interaction	Biomedical, analytical and catalytic application	[89]
24	Plasmid DNA	Calcium phosphate	Organic–inorganic nanoparticle conjugates	Encapsulation	Stem cell uptake and gene transfer	[90]
25	Pepsin	AuNP	Organic–inorganic nanoparticle conjugates	Covalent-amide coupling	Analytical sample preparation	[91]
26	Propolis	Lipid	Organic–organic nanoparticle conjugates	Entrapment	Nasal drug delivery	[92]
27	Quercetin	Chitosan oligosaccharide/ β-lactoglobulin	Organic–organic nanoparticle conjugates	Covalent	Encapsulation of bioactives	[61]
28	Serum albumin	PCL/PLGA	Biomolecule–polymeric nanoparticle conjugates	Encapsulation	Delivery of therapeutics	[93]
29	Sericin	Copper(II) phosphate	Self-assembled biomolecule–nanoparticle hybrid	—	Adsorption of heavy metal ions	[94]
30	Spherical nucleic acid	AuNP	Organic-inorganic nanoparticle conjugates	Covalent	Cellular uptake	[95]
31	Sorafenib	PEG-PLGA/PLGA copolymer	Biomolecule–polymeric nanoparticle conjugates	Encapsulation	Systemic treatment of liver fibrosis	[96]
32	Trypsin	AuNP/Fe_3O_4	Biomolecule–hybrid nanoparticle conjugates	Covalent	Enzymatic digestion of proteins to peptides	[97]
33	Xylanase	Fe_3O_4/SiO_2	Biomolecule–hybrid nanoparticle conjugates	Covalent	Enzymatic clarification of fruit juices	[98]

Low-molecular-weight bifunctional linkers are used to form a covalent linkage between biomolecules and NPs. These linkers encompass thiols, disulfides, and phosphine ligands, coupled with terminal functional groups such as carboxy, amino, or maleimide groups. They facilitate the conjugation of biomolecules to common NPs, including Au (gold), CdS, ZnS, CdSe/ZnS, and Ag (silver), enabling the formation of stable complexes for various biomedical and nanotechnological applications [101, 106].

1.3.2 Organic–Organic Nanoparticle complexes

Biological NPs have the capability to form complexes with other biological NPs through encapsulation. These encapsulated bio-nanomaterials find numerous applications across industries such as food, pharmaceuticals, and cosmetics. For instance, β-carotene, a highly photosensitive compound, can be encapsulated within whey protein concentrate (WPC) using techniques such as electrospraying. The resulting nanocomplex of β-carotene/WPC exhibits exceptional stability against photo-oxidation, making it suitable for various applications in food and pharmaceutical formulations [75].

Similar encapsulation strategies can be followed for bioactive molecules such as curcumin, quercetin, and (−) epigallocatechin-3-gallate (EGCG). These highly unstable compounds are encapsulated with chitosan-based NPs. Chitosan NPs are more stable as compared to chitosan, so the encapsulation is better in the case of NPs as compared to whole chitosan [61, 79, 83].

1.3.3 Biomolecule–Polymer Nanoparticle Complexes

Biocompatible and biodegradable polymers such as poly(ethylene glycol) (PEG), poly(lactic acid) (PLA), polyglycolides (PGA), poly(lactide-*co*-glycolides) (PLGA), polycaprolactone (PCL), and poly(hydroxy butyrate) (PHB) are extensively employed due to stimulus-responsive properties and robust mechanical strength. These polymers are utilized in the fabrication of biomolecule–polymer conjugates, resulting in nanostructures suitable for drug delivery applications [109–111].

The complex formed between a polymer and biomolecules usually consists of two layers: an outer shell comprising biocompatible biomolecules and an inner shell composed of a hydrophobic polymer that can encapsulate drugs. A prime example of such a complex nanostructure is the FDA-approved thermoplastic hydrophobic polymer poly-methyl methacrylate (PMMA) combined with bovine serum albumin (BSA) [112]. Employing the nanoprecipitation technique, particles of 100 nm size are synthesized, with their dimensions and surface charge controlled by adjusting the concentration of BSA and PMMA. Encapsulation of the hydrophobic drug camptothecin showcased improved antitumor efficacy.

1.3.4 Organic–Inorganic Complex

Inorganic NPs, such as metals, metal oxides, and quantum dots, exhibit unique optical, electronic, and catalytic properties. Their conjugation with biomolecules such

as DNA, enzymes, antibodies, and peptides plays a crucial role in pharmaceutical industries, therapeutics, and diagnostics. Among these, gold (Au) NPs are extensively studied. The surface chemistry of gold NPs is meticulously regulated through the utilization of biomolecules, opening avenues for the advancement of next-generation nanoscale complexes. For instance, Au NPs hybridized with the fungal protein hydrophobin (HFB) Vmh2 yield stable HFB–AuNP complexes. These complexes can effectively interact with biomolecules such as BSA and immunoglobulins, offering promising applications in various biomedical and diagnostic fields [113].

Similarly, enzymes can be integrated onto the surface of inorganic NPs, which results in a highly stable enzyme complex [114]. For instance, when pepsin is bound to Au NPs via amide coupling, it forms a stable and efficient biocatalyst. This biocatalyst has applications in the analysis of therapeutic proteins and peptides, showcasing the versatility and potential of Au NP–biomolecule conjugates in various biomedical and pharmaceutical contexts [91]. Moreover, these complexes offer the advantage of incorporating multiple enzymes into a single NP. For example, a multienzyme complex comprising alpha-amylase, pectinase, and cellulase can be functionalized onto magnetic NPs. This enables the clarification of fruit juice turbidity, demonstrating the potential of enzyme-functionalized NPs in various industrial applications, particularly in food processing and beverage production [69].

1.3.5 Self-Assembled Biomolecule–Nanoparticle Complex

Self-assembly is an innovative technology wherein various components of an integrating complex are fabricated in a desired order. A study demonstrated that when proteins are incorporated into nanostructure construction, it results in the formation of flower-like nanostructures. This exemplifies the power of self-assembly techniques in engineering complex and functional nanomaterials with tailored properties for diverse applications in nanotechnology and biomedicine [115]. Indeed, the formation of flower-like nanostructures is attributed to protein-induced nucleation of copper phosphate crystals during the self-assembly process. Similarly, self-assembly phenomena are observed in DNA nanostructures. The complementary nature of DNA strands allows for the precise and facile manipulation of size and shape in these self-assembled nanostructures. This inherent programmability makes DNA nanostructures a versatile platform for engineering complex and customizable nanomaterials with tailored functionalities for a wide range of applications in nanotechnology and biomedicine. Geometrically nanostructured shapes have been developed for various applications, including DNA cubes, knots, polyhedra, and nanotubes. These DNA nanostructures are utilized for mechanical motions and computational studies, showcasing the versatility and potential of DNA-based nanotechnology in engineering intricate and functional nanomaterials for diverse applications in nanotechnology, biomedicine, and beyond [116].

Peptide self-assembly has emerged as a promising field in nanomedicine, offering diverse benefits for biomedical applications [117–121]. By employing rational design strategies, various peptide-based supramolecular architectures such as micelles,

vesicles, and nanofibers can be synthesized, with each structure being governed by noncovalent interactions [47]. The inherent amphiphilicity of peptides, with polar and nonpolar regions, facilitates their self-assembly through microphase separation [122, 123]. Noncovalent interactions, including hydrophobic and ionic interactions, van der Waals forces, hydrogen bonds, and π–π stacking, serve as the primary driving forces for self-assembly [122]. For gene delivery, peptide nanoassemblies consist of hydrophobic amino acids driving self-assembly, hydrophilic amino acids.

Peptide self-assembly has emerged as a promising avenue in nanomedicine, owing to the manifold benefits offered by well-defined applications Nanoassemblies, derived from common amphiphilic peptides and peptide conjugates [117–121], encompass a range of supramolecular structures suitable for biomedical applications. These structures include linear, ionic complementary, long-chain alkylated, and lipo-peptides [124]. In contrast to individual peptides, peptide self-assemblies exhibit distinctive attributes such as multivalent binding, dynamic cargo interactions, responsiveness to environmental and cellular stimuli, and prolonged functionality. Through a systematic design of molecular building blocks, various peptide-based supramolecular architectures – such as micelles, vesicles, nanofibers, nanotubes, and NPs – can be synthesized [125]. The inherent amphiphilicity of peptides, with polar and nonpolar regions, facilitates their self-assembly through microphase separation [122, 123].

Various noncovalent interactions, such as hydrophobic and ionic interactions, van der Waals forces, hydrogen bonds, and π–π stacking, serve as the primary driving forces behind self-assembly [122]. For instance, aromatic residues predominantly contribute to self-assembly through π–π stacking, while hydrogen bonding plays a crucial role in the formation and stabilization of secondary structures. Peptides exhibiting stable β-strand conformations have the propensity to form extended β-sheet structures through lateral connections, crucial for the formation of nanofibers and nanotubes. Within these β-sheets, hydrophobic side chains align in one direction, while polar side chains align in the opposite direction [126]. Conversely, α-helical structures promote the formation of micelles and vesicles, where hydrogen bonding occurs between the carbonyl group of one amino acid and the amino group of four residues down the peptide chain. The outward orientation of amino acid side chains in α-helices enables interactions [125]. Well-defined peptide nanoassemblies for gene delivery comprise three fundamental components: hydrophobic amino acids facilitate self-assembly through intermolecular noncovalent interactions and subsequent secondary structure formation; hydrophilic amino acid residues stabilize the structure in a biological environment; and positively charged amino acid residues interact electrostatically with negatively charged nucleic acids [47]. In contrast, peptide NPs, referred to as peptiplexes, spontaneously form via electrostatic interactions between positively charged peptide residues (lysine, arginine, and histidine) and negatively charged nucleic acids [127].

Furthermore, chemical structures of peptides are engineered to yield nanoassemblies tailored specifically for diagnostic imaging [128], focusing on two crucial aspects: the peptide's targeting property and functionalization with a detectable moiety [129]. This approach leverages the unique properties of peptides to design and fabricate nanomaterials with precise control over size, shape, and surface

properties, enabling their use as contrast agents for various imaging modalities such as magnetic resonance imaging (MRI), computed tomography (CT), and fluorescence imaging. These peptide-based nanoassemblies hold promise for improving the sensitivity and specificity of diagnostic imaging techniques, facilitating early disease detection and monitoring.

The self-assemblies result in various structures. Vesicles, spherical hollow structures delimited by bilayers, are formed from one or more types of amphiphilic molecules [125]. Hydrophilic regions are oriented toward both inner and outer aqueous environments, while hydrophobic residues pack together between these hydrophilic interfaces [130]. Consequently, vesicles have the capability to encapsulate hydrophilic molecules within their interior aqueous phase and hydrophobic molecules within the hydrophobic regions of the bilayer [131]. Modifying the composition and chain length of the building blocks enables the adjustment of the size of vesicles [132]. Self-assembly of pure amphiphilic oligopeptides [133] and diblock copolypeptides [134, 135] results in the formation of vesicles in aqueous solution. The propensity of peptides to assemble into vesicles or nanotubes is largely influenced by the hydrophobicity of their tails. Additionally, surfactant-like peptides featuring a hydrophilic head domain comprise aspartic acid residues and a hydrophobic tail composed of 4–10 glycine residues have been observed to self-assemble into vesicles with diameters of approximately 30–50 nm [136, 137].

Peptide-based nanovesicles provide several advantages over liposomes, including enhanced membrane fluidity, targeting ability, biocompatibility, and stability, attributed to the inherent chemical and biological properties of peptides [138, 139]. Peptide-mediated targeting and safeguarding cargo against extracellular threats are particularly critical for in vivo DNA delivery. Improving DNA stability and extending circulation time facilitate superior organ distribution [140, 141].

Self-assembled peptide vesicles (SPVs) undergo diverse chemical modifications, including conjugation of other peptides or bioactive molecules to the outer surface as well as encapsulation of specific cargoes within the aqueous cavity or the hydrophobic domain of the membrane [142, 143]. An example of such a multifunctional SPV platform involves the conjugation of the epidermal growth factor receptor (EGFR) binding peptide GE11 to glycidyl hexadecyl dimethyl ammonium chloride (GHDC).

Peptide nanotubes (PNTs) represent intricate three-dimensional structures, maintaining a distinct hollow cylindrical form through molecular interactions among their amphiphilic building blocks [144]. These PNTs offer vast potential for functionalization, particularly at the head group of peptide amphiphiles, making them versatile candidates for diverse applications [145]. As the hydrophobic alkyl chains align toward the core and the amino acid residues toward the outer surfaces, functional groups become accessible on the outer surfaces of PNTs [146].

Peptide-based micelles, considered one of the leading self-assembly nanostructures in biomedicine, comprise closed monolayers characterized by a hydrophobic inner core encased within a hydrophilic outer shell. Two primary methods for micelle preparation are direct dissolution and solvent switch. The spontaneous formation of these precisely structured spherical assemblies, with a narrow size distribution, takes place above a critical micellar concentration (CMC) and may be influenced by temperature [147, 148].

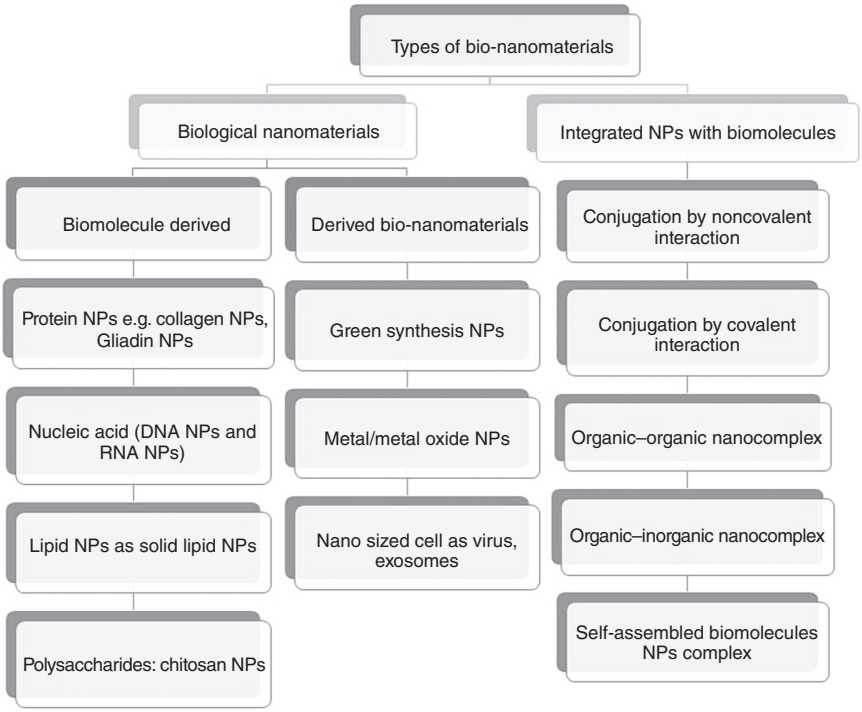

Figure 1.2 Classification of bio-nanomaterials. The figure presents a classification scheme for bio-nanomaterials based on their composition, structure, and synthesis methods. This classification scheme provides a comprehensive overview of the diverse landscape of bio-nanomaterials, guiding future efforts toward innovative applications and solutions.

Overall classification of bio-nanomaterials is represented in Figure 1.2.

1.4 Application of Bio-nanomaterials

1.4.1 Clinical Application

The plethora of research focused on the development of various types of bio-nanomaterials has led to a rise in the number of therapeutics for both diagnosis and treatment of diseases. These advancements have propelled the field of nanomedicine forward, offering innovative solutions for targeted drug delivery, imaging, and diagnostics. As a result, bio-nanomaterials hold great promise for improving patient outcomes and revolutionizing healthcare practices in the near future. The lipid NP-encapsulated drug delivery shows better drug release and it is targeted to the specific area. This precise drug delivery minimizes the possibility of side effects and reduces the frequency of drug administration [149].

Cancer Treatment and Diagnosis: There are a number of studies to develop bio-nanomaterials to combat cancer. In one study, a bio-nanomaterial is synthesized using gold NP packed with effector protein (SipA), from *Salmonella*

enterica. Bio-nanomaterials have demonstrated the ability to suppress tumor growth by effectively reducing the expression of P-glycoprotein, a multidrug resistance transporter, at significantly lower doses compared to free SipA. This reduction in P-glycoprotein expression enhances the effectiveness of chemotherapeutic agents, showcasing the potential of bio-nanomaterials in overcoming drug resistance mechanisms and improving the efficacy of cancer treatments [150]. The surface resonance property of Gold NPs' is utilized to target and bind to prostate cancer biomarkers, causing a detectable change in their SPR(surface plasmon resonance) characteristics. This alteration, measured through techniques such as spectrophotometry, enables accurate and minimally invasive diagnosis of prostate cancer, promising improved patient outcomes through early detection. Gold NP is conjugated with prostate-specific antibodies (PSAs) and when these particles bind to the cancer cells, the NPs come together and show color change due to surface plasmon resonance [151]. Protein and polysaccharides have the potential to be used as vehicles in NP-mediated delivery systems [83, 152]. Antioxidant phytochemicals can be effectively encapsulated within bio-nanomaterials, facilitating their targeted delivery without compromising their anticancer properties.

Encapsulating EGCG with biocompatible NPs derived from bioactive peptide/chitosan greatly improves EGCG's bioavailability, enhancing its potential therapeutic effects. This innovative approach improves the delivery of EGCG, a potent antioxidant found in green tea, by protecting it from degradation and improving its absorption in the body. This encapsulation strategy holds promise for enhancing the therapeutic potential of EGCG in various biomedical applications [83]. Bio-nanomaterial-based carriers enable the simultaneous delivery of multiple drugs, leading to a synergistic effect. This approach is especially advantageous in cancer therapy, as tumor microenvironments, with their pH gradients, present challenges for conventional drug delivery. Encapsulation within bioactive peptide/chitosan NPs enhances EGCG's efficacy by overcoming these barriers, potentially improving cancer treatment outcomes. To address this, pH-responsive drug delivery systems have been developed, employing mussel adhesive protein (MAP)-based iron (III)-3,4-dihydroxyphenylalanine (DOPA) NPs. These systems capitalize on the pH sensitivity of MAPs and DOPA to trigger drug release in the acidic tumor microenvironment, thereby boosting the effectiveness of cancer therapies while reducing unintended side effects [153].

The shape of NPs plays a significant role in therapy, especially in applications such as bone regeneration. NPs synthesized from gelatin and hydroxyapatite with a spherical topology have been found to enhance bone formation compared to other shapes. This can be attributed to their capacity to mimic the natural structure of bone minerals, fostering interactions with bone cells and thereby enhancing osteogenesis and bone regeneration more efficiently. Such findings underscore the importance of NP shape in tailoring therapeutic outcomes and optimizing treatments for specific biomedical applications [154]. Bio-nanoparticles possess the potential to supplant traditional carriers in drug delivery applications. Utilizing protein NPs as drug carriers has demonstrated the ability to facilitate efficient transport across the

blood–brain barrier, addressing a pivotal challenge in the treatment of neurological disorders. These protein NPs offer several advantages, including biocompatibility, targeted delivery, and the ability to encapsulate and protect drugs from degradation. Researchers are leveraging the distinctive properties of bio-nanoparticles to develop more efficient and precisely targeted therapies for neurological disorders [155].

1.4.1.1 Drug Delivery System

Protein cages are intricate structures formed by the self-assembly of individual protein monomers, distinct from viral components. They include VLPs and VNPs, each with unique characteristics. VLPs lack viral genomes and are considered noninfectious, potentially eliciting different immunostimulatory responses compared to VNPs. These structures, comprising repeating protein subunits, offer high multivalency. Plant viruses can exhibit spherical/icosahedral or filamentous/tubular shapes. Viruses, with their innate ability to carry nucleic acids, serve as optimal vehicles for drug delivery. They offer versatility in binding active molecules through infusion, encapsulation, absorption, or conjugation to protein interfaces, ensuring protection and enabling precise targeting of the intended site of action [66].

Although clinically approved nanomedicines based on plants or bacteriophages are currently absent, numerous candidates are undergoing preclinical development, with several progressing toward translational development. Prominent platforms include tobacco mosaic virus (TMV), cowpea mosaic virus (CPMV), cowpea chlorotic mottle virus (CCMV), physalis mottle virus (PhMV), potato virus X (PVX), and bacteriophages such as MS2, P22, Qβ, and M13. Ranging in size from approximately 30 nm to over a micron, these viruses exhibit diverse shapes. Advancements in biochemistry and directed evolution techniques have propelled the development of viral nanocarriers for drug delivery, imaging, and theranostic applications. This review underscores the utilization of VNPs and VLPs in diverse biomedical domains, spanning antimicrobial treatments, cancer therapies, protein/peptide delivery, gene therapies, monotherapy, and combination cancer treatments as well as vaccines for infectious diseases, cancer, and other conditions. Additionally, it explores their role in imaging modalities and theranostics, integrating photothermal therapy (PTT) [66].

1.4.1.2 Lipid-Based Approved Nanopharmaceuticals

Liposomes, as pioneering drug delivery systems, remain widely utilized due to their versatile composition, biocompatibility, biodegradability, and lack of immunogenicity. These artificial phospholipid vesicles typically range from 50 to 100 nm in size, with anionic, cationic, or neutral variants, and feature a central aqueous phase. While liposomes predominantly encapsulate hydrophilic drugs within their aqueous core, they can also accommodate hydrophobic drugs in their bilayer or chemically attach them to the particles. In contrast, micelles, another phospholipid-based structure, possess a hydrophobic core ideal for encapsulating hydrophobic drugs and are employed for targeted drug delivery to specific sites, thereby reducing bio sdistribution toxicity.

The initial generation of liposomes exhibited limitations in blood circulation time and tumor tissue-specific targeting due to uptake by the mononuclear phagocyte

system (MPS), leading to accumulation primarily in the liver and spleen. However, advances in lipid selection and modification techniques, such as sterically stabilizing nanoliposomes with sphingomyelin/choline (SM/CHO) and coating with PEG, known as pegylated or Stealth liposomes, have overcome these challenges. Pegylated liposomes demonstrate prolonged circulation time, enhanced extravasation through leaky tumor vasculature via passive targeting, reduced uptake by reticuloendothelial system (RES) cells, and decreased drug leakage in circulation. These modifications facilitate drug accumulation in tumor tissue, significantly improving upon the limitations of the first generation of liposomes.

Various lipid-based nanotechnology platforms have yielded approved nanopharmaceuticals, with Doxil™ being the first FDA-approved in 1995, followed by Caelyx™ and Myocet™, which encapsulate the chemotherapeutic doxorubicin. These formulations, including pegylated and nonpegylated versions, were developed to mitigate the high cardiotoxicity associated with doxorubicin. By extending circulation time and reducing distribution volume, they enhance tumor uptake through the enhanced permeability and retention (EPR) effect, improving tumor therapy efficacy. DaunoXome™ encapsulates Daunorubicin, protecting it from degradation and enhancing its accumulation in tumors, particularly indicated for advanced HIV-associated Kaposi's sarcoma. Mepact™, an immunomodulator, is indicated for treating high-grade resectable nonmetastatic osteosarcoma. Ameluz™, a nanoemulsion gel containing 5-aminolaevulinic acid, is activated by red light to treat actinic keratosis. Marqibo™, an NP formulation of Vincristine, reduces neurotoxicity and is indicated for advanced acute lymphoblastic leukemia. Onivyde™, encapsulating Irinotecan, is indicated for metastatic adenocarcinoma of the pancreas. Vyxeos™, a liposomal formulation of Daunorubicin and Cytarabine, is used for high-risk acute myeloid leukemia treatment. These nanopharmaceuticals showcase the versatility and efficacy of lipid-based nanotechnology in drug delivery [156].

1.4.1.3 Protein-Based Approved Nanopharmaceuticals

Protein-based NPs present numerous advantages, including biocompatibility and biodegradability, with fibroin and albumin frequently employed. They have the capacity to transport diverse therapeutic agents, encompassing genetic materials, anticancer drugs, and peptide hormones. Several protein-based NPs have received approvals from the FDA and EMA for cancer treatment. Examples include OncasparTM for acute lymphoblastic leukemia, OntakTM for cutaneous T cell lymphoma, and AbraxaneTM and PazenirTM for metastatic breast cancer and other solid tumors. These NPs provide targeted delivery, reducing toxicity and enhancing antitumor activity. Additionally, KadcylaTM, an antibody–drug conjugate, is approved for HER2-positive breast cancer. Overall, protein-based NPs show promise for advanced cancer therapy, with numerous options approved by regulatory agencies [157, 158].

Peptide-based micelles offer distinct advantages in gene delivery, such as remarkable stability, efficient gene loading capability, and small size, enabling effective tumor penetration and cellular uptake. Cationic micellar nanoassemblies efficiently condense nucleic acids, exemplified by cationic peptide dendrimers and

amphiphilic peptides, which exhibit superior delivery efficacy compared to conventional transfection agents. These micelles are customizable to target specific cells, promoting cellular uptake, facilitating endosomal escape, and enabling transport to the nucleus. Amphiphilic cationic peptides self-assemble into micelles with robust DNA-binding affinity, effectively shielding DNA and elevating gene expression levels in contrast to alternative complexes. These peptides exhibit a dual nature, with hydrophobic and hydrophilic regions, enabling the formation of stable micellar structures that efficiently encapsulate DNA. This unique architecture enhances the protection of DNA payloads during transportation and facilitates their delivery to target cells, ultimately leading to heightened gene expression levels. Peptide constituents offer the versatility to engineer vesicles responsive to environmental cues or external triggers. For instance, cationic vesicles containing drugs like Doxorubicin exhibit pH-triggered cargo release, while pH- and temperature-sensitive vesicles derived from specific copolypeptides respond to variations in their surroundings. Additionally, surfactant-like peptides have the capacity to self-organize into nanotubes, forming robust hierarchical architectures conducive to gene delivery owing to their positively charged characteristics. Hybrid nanotubes combining peptides with polymers or lipids are being investigated for diverse biomedical purposes, particularly in gene delivery, capitalizing on their nontoxic attributes and adaptable architectures. These hybrids offer a synergistic combination of the unique properties of peptides with the functionalities of polymers or lipids, enhancing their efficacy and versatility in biomedical applications.

Polysaccharide NPs hold promise in biomedicine and biomaterials engineering, particularly for their inherent biocompatibility and biodegradability. These NPs are uniquely positioned for a spectrum of applications in nanomedicine, including drug delivery and tissue engineering, harnessing characteristics such as mucoadhesion and cellular uptake to optimize therapeutic outcomes. Recent developments include their use in photodynamic therapy (PDT). One approach involved chitosan (CS)-based NPs conjugated with the photosensitizer Pheophorbide A, which self-quenched in aqueous environments but released the photosensitizer upon exposure to reactive oxygen species in tumor environments, leading to cell death upon near-infrared irradiation. Another PDT approach utilized a fully polysaccharide-based block copolymer composed of dextran (DEX) and acetylated DEX blocks, encapsulating a photosensitizer. This block copolymer stabilized the photosensitizer, enhancing its bioavailability, and showed concentration-dependent toxicity upon NIR irradiation. Moreover, dextran nanoparticles (DEX NPs) conjugated with folic acid have been scrutinized for their potential to enhance targeted uptake into cancer cells, thereby augmenting the effectiveness of PDT [63].

1.4.2 Clinical Diagnosis and Bioelectronics

The exceptional chemical and physical properties of NPs have broadened opportunities in the field of sensors. NPs present numerous advantages, including high surface-to-volume ratios, customizable optical and electronic characteristics, and heightened responsiveness to alterations in their environment. These properties

make NPs ideal candidates for sensor development across various applications, including environmental monitoring, healthcare diagnostics, and industrial process control. The size of NPs does impart a varied conducting property, optical property, and physiochemical property. Taking advantage of these, various sensing devices have been proposed that can detect the molecule at a picomolar level. The sensing could be of some disease biomarkers, contaminants in the food and agriculture sector, microbes (virus and bacterial) detection in samples, gas leakage detection, and detection of nucleic acids. There is a plethora of research undergoing in developing diagnostic devices using nanomaterial hybridized with biomolecules.

For early detection of epithelial tumors, a biosensor has been generated using gold NPs on which hairpin oligonucleotide (HO) and horseradish peroxidase (HRP) are immobilized [159]. The intricate assembly of HO-AuNP-HRP serves as a versatile platform for implementing a multitiered signal amplification approach, facilitating swift detection and heightened sensitivity. Surface modification of the biosensor with carbon nanotubes expedites electron transfer, while the HO-AuNP-HRP enzyme acts as a traceable label for electrochemical detection. Early detection of cancer could be achieved by detecting siRNA. For siRNA detection, modified oligonucleotides are used. The method known as nucleic acid detection is a target-assisted proximity proteolysis reaction. The two oligonucleotides are designed along with the two units of protease. The arrangement is such that this protease will not be active until siRNA binds to the oligonucleotide (close proximity). This can detect the small-interfering RNA in the early stages of breast cancer.

The immobilized enzyme NPs are capable of detecting glutamate and GABA, essential neurotransmitters that regulate excitatory and inhibitory postsynaptic currents. The sensor integrates ceria and titania NPs within a semipermeable membrane crafted from chitosan. Glutamate oxidase (GmOX) is coimmobilized with chitosan on a platinum electrode. This setup enables precise and sensitive detection of neurotransmitters, showcasing promising utility in neuroscience investigations and clinical diagnostic settings [160].

Another example of enzyme-based biosensors, glucose concentration is detected by using immobilized NPs of iron oxide, glucose oxidase (Gox), and polypyrrole onto the surface of glassy carbon electrode [84].

Bio-nanomaterials, particularly nucleic acid complexes, are instrumental in developing nanomachine-like devices, memory storage systems, and scaffolds for tissue engineering. These DNA nanodevices are constructed based on base-pairing interactions, the distinct mechanical strength of single and double strands, and the electrostatic properties of DNA and RNA as highly charged polyelectrolytes. Nanomechanical DNA devices' motions are propelled by conformational shifts triggered by changes in buffer composition or the binding of complementary DNA strands. These nanoscale mechanical changes, stemming from transitions between single-stranded DNA and duplex DNA, enable precise nanoscale complex design for synthesizing NPs, thereby aiding in addressing fundamental structural biology and biophysics questions.

Furthermore, DNA origami, which entails the formation of 2D and 3D DNA nanoscale structures, can replace liquid crystals in residual dipolar coupling

experiments. This technique facilitates the determination of the nuclear magnetic resonance (NMR) structure of membrane proteins in detergent-rich solutions. DNA origami is also utilized in nanoenzyme folding and functionality studies as well as in nanoelectronics for designing precise nanowires. Moreover, DNA NPs can be utilized for drug delivery applications, as they have the capability to undergo assembly and disassembly, with conformational alterations facilitating drug release. Overall, the versatility and programmability of DNA-based nanomaterials offer a plethora of opportunities for advancing various fields of science and technology. Aptamers, another category of bio-nanoparticles, play a crucial role in detecting peptides, proteins, and biomarkers. These single-stranded DNA and RNA molecules possess the ability to selectively bind with a wide array of targets, including proteins, peptides, carbohydrates, small molecules, toxins, viruses, bacteria, and exosomes. Aptamers have found widespread application in diagnostic procedures.

Bio-nanomaterials are used for the development of nanoscale memory devices. A bio-nanomaterial complex is fabricated using azurin (a redox protein) and quantum dot (CdSe-ZnS). A mutation is induced in azurin so that CdSe-ZnS can bind to the protein. This complex can act as a resistive random access memory (ReRAM) device with change in voltage, having the ability to repeatable writing–reading [161].

1.4.2.1 Regenerative medicine

Currently, clinical vascular grafts primarily rely on autologous blood vessels. However, the limited availability of such vessels poses a challenge. Synthetic alternatives such as polytetrafluoroethylene (ePTFE) are frequently employed, and they are plagued by complications such as thrombosis and intimal hyperplasia, resulting in suboptimal long-term patency rates. As a result, they fail to meet the stringent clinical requirements. To address this, advancements in nanomaterials, stem cells, and 3D bio-printing have spurred exploration into novel endothelialized vascular grafts. Nano-peptide materials, known for their exceptional biocompatibility and ability to incorporate various bioactive molecules, offer promise in cultivating stem cells. Recent studies have demonstrated the successful construction of self-assembled nano-polypeptide hydrogels, enabling the isolation, culture, and differentiation of mesenchymal stem cells into blood vessels. These advancements highlight the potential of integrating mesenchymal stem cells with nano-polypeptide hydrogels in tissue engineering for blood vessels, marking a rapidly expanding area of research. This approach holds the potential to create transplanted blood vessels that align with physiological functions, offering customized and personalized solutions through endothelialized printing tailored to specific vessel shapes. Such innovations carry significant social and economic implications, offering promising prospects for better patient outcomes and more effective treatment [162].

The quest for an ideal vascular tissue scaffold material has led to the exploration of nanoscale biomaterials synthesized from polypeptide molecules. These materials offer advantages over traditional options, such as better biocompatibility, degradability, and the ability to incorporate bioactive molecules, imparting them with "biological intelligence." Researchers have focused on self-assembling nano-polypeptide hydrogels, which form frame structures ideal for cell growth

and migration. These hydrogels, composed of polypeptides like RADA16, exhibit promising characteristics for tissue engineering, including good biocompatibility and the ability to induce stem cell differentiation into blood vessels. Studies have demonstrated their potential as "biological ink" for 3D biological printing, showcasing their application in regenerative medicine and stem cell transplantation. However, challenges such as mechanical properties and hydrophilicity still need to be addressed, prompting ongoing research into modifications to enhance the performance of these materials in tissue engineering [163].

Functional targeting of nanovehicles can be accomplished through two main strategies: active targeting and stimuli-responsive targeting. Active targeting entails engineering nanovehicles to selectively target cells by leveraging molecular recognition mechanisms, like ligand–receptor interactions, commonly found on tumor cells. Ligands with high affinity for receptors trigger receptor-mediated endocytosis, facilitating intracellular release. Common ligands include folic acid, peptides, antibodies, cell-penetrating peptides (CPPs), growth factors, and cytokines. Antibodies, particularly antigen-binding fragments (Fabs), are effective but costly to produce. Alternatively, aptamers, small synthetic oligonucleotides, offer versatility and specificity in binding various targets. They are simpler and more cost-effective to prepare, with no apparent toxicity concerns.

1.4.2.2 Nanopeptides as Diagnostics

Nanoprobes must exhibit molecular specificity to be clinically useful, particularly in molecular imaging and disease diagnosis, where protein expression and activity profiles serve as valuable biomarkers. Peptide-based materials are preferred for creating nanoprobes due to their ability to perform various functions through sequence variation, secondary structures, and side chain modifications. Peptides offer easy chemical synthesis and superior biocompatibility, making them ideal for biomedical applications. Peptide-based nanoprobes (PBNs) facilitate effective molecular imaging by optimizing target-to-background selection through enhanced accessibility, affinity, and retention within targeted molecules. Moreover, enzymatic-mediated peptide cleavage and modification enable specific switching of nanoprobes ON/OFF to detect enzyme activity. Peptides can be fine-tuned to attain high contrast and specificity, providing precise and accurate molecular imaging for diagnostics and various biomedical applications.

Self-assembled peptide-based micelles have shown promise in disease diagnosis, particularly in cancer detection. Novel micelles formulated from C-3 peptide linked with a nitrobenzoxadiazole (NBD) fluorophore have been engineered to target cancer cells exhibiting elevated furin expression, presenting a promising avenue for early cancer detection. Furthermore, peptide-based micelles have the capability to integrate both diagnostic and therapeutic functionalities. For instance, amphiphilic peptide conjugates, such as Cy7-CREKA micelles, demonstrated tumor-homing capabilities in mouse models, accumulating at the tumor site without causing cytotoxicity or tissue damage. Similarly, peptide-based micelles conjugated with LyP-1 peptide exhibited pronounced accumulation at tumor sites, facilitating effective delivery of NPs into tumors. Peptide nanofibers (PNFs) also hold promise for

theranostic applications, with gold nanoclusters (AuNCs) enhancing luminescence efficiency in fluorescence imaging. Additionally, PNFs coassembled with peptide amphiphiles improved contrast in MRI, showcasing their potential as nanoprobes for MRI.

1.4.3 Food Industry

The advances in the usage of bio-nanomaterials are visible in the fields of diagnostics, nanomedicine, and biosensors, but there is still room for the growth in food and packaging industry (Figure 1.3). There is an increase in the trend of usage of bio-nanotechnology in the past few years in food industries [164].

Bio-nanomaterials are used as a carrier for the nutrient, increasing the bioavailability. This method becomes important in the case of gastrointestinal diseases. NPs play a crucial role in enhancing the bioavailability of poorly soluble bioactive compounds by encapsulating them with biomolecules. This encapsulation process improves the solubility, stability, and delivery of the bioactive compounds, ensuring their effective absorption and utilization within the body. By acting as carriers, NPs protect the encapsulated compounds from degradation in the gastrointestinal tract and facilitate their transport to target sites, thereby maximizing their therapeutic efficacy. Overall, NP-based encapsulation strategies represent a promising approach for overcoming the challenges associated with poorly soluble bioactive compounds and enhancing their bioavailability for improved health outcomes.

Chitosan and whey protein are the most common biomolecules used for encapsulating nutraceuticals, probiotics, enzymes, and bioactive food ingredients.

The food packaging sector also uses bio-nanomaterials for preventing the spoilage of food. The incorporation of the nanomaterial could provide an efficient food preservation system by scavenging oxygen and prevent spoilage by antimicrobial

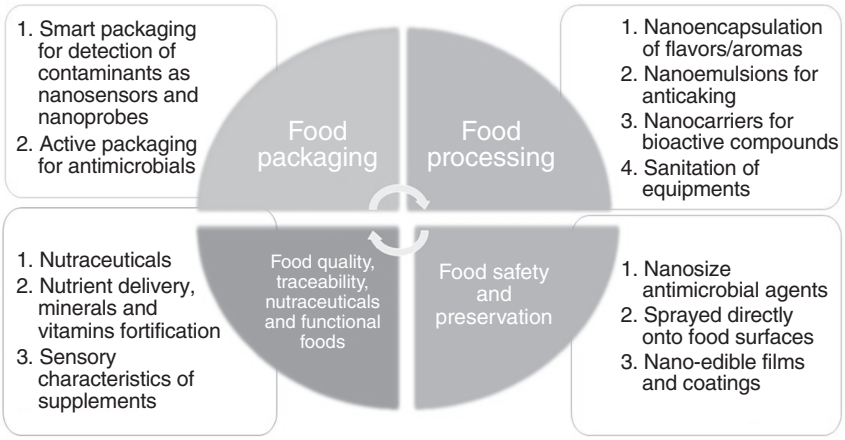

Figure 1.3 Bio-nanomaterials in the food industry. The figure showcases the multifaceted applications of bio-nanomaterials in food technology, including food packaging for preservation, food processing, rapid detection of contaminants, and enhancing nutrient delivery for improved food quality and safety.

properties. For instance, a bio-nanomaterial packaging complex is a form of whey protein and montmorillonite NP activated with lycopene; this shows improved antioxidant activity, UV-light protection, and barrier against water vapor [165].

Food Packaging: Nanocomposite films' bio-nanomaterials, such as nanoclays, cellulose nanocrystals, or chitosan NPs, that are incorporated into packaging materials to enhance barrier properties, mechanical strength, and overall performance. Antimicrobial nanomaterials with antimicrobial properties, like silver NPs, are used to develop packaging films that inhibit the growth of bacteria and extend the shelf life of perishable foods [166].

Food Processing: Nanocarriers for nutrients including liposomes and nanoemulsions are employed as carriers for nutrients, vitamins, and bioactive compounds, enhancing their stability and bioavailability in food products. Nanoencapsulation is used to encapsulate flavors, colors, and functional ingredients, protecting them from degradation during food processing and storage [167].

Food Safety: The quick and sensitive identification of pollutants, pathogens, and allergens in food items is achieved through the use of nanosensors and nanoprobes. Bio-nanomaterials' Smart Packaging helps create smart packaging that provides real-time information on the state of food by using indicators that change color in response to temperature, freshness, or the presence of certain gases [168].

Food Preservation: Antimicrobial NPs are nanosized antimicrobial agents, such as zinc oxide or titanium dioxide NPs, are incorporated into food packaging or sprayed directly onto food surfaces to prevent microbial growth and spoilage. Edible coating or edible films are coatings based on bio-nanomaterials that are applied to fruits and vegetables to extend their shelf life by creating a protective barrier against moisture, oxygen, and pathogens [169].

Food Quality and Traceability: Bio-nanomaterial-based biosensors are used for detecting foodborne pathogens, toxins, and contaminants, ensuring the quality and safety of food products. Nanotracers can be used as traceable markers to monitor the origin, processing, and distribution of food products, contributing to traceability and quality control [170].

Nutraceuticals and Functional Foods: Nanocarriers for drug delivery are employed as carriers for delivering nutraceuticals and bioactive compounds, enhancing their absorption and bioavailability in the human body. Nanoencapsulation of bioactives utilized to encapsulate bioactive compounds protects them from degradation and provides controlled release in functional foods [171].

1.4.4 Utilities of Bio-nanomaterials for Environment Remediation

The convergence of energy shortages and environmental pollution presents a critical global challenge, compounded by population growth, globalization, and industrial expansion. Urgent action is imperative to avert a looming crisis in natural resource depletion within the next 20–30 years. Presently, efforts are being made to devise sustainable materials that enhance human lifestyles while

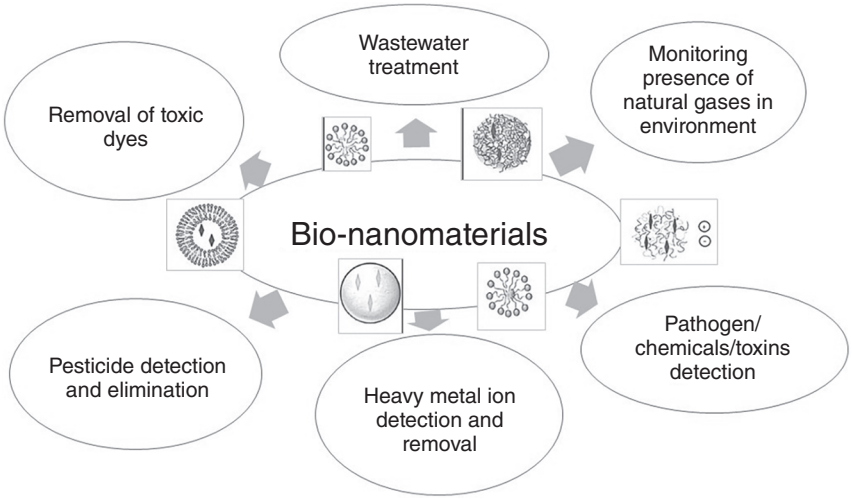

Figure 1.4 Versatility of bio-nanomaterials in environmental applications. The diagram highlights the diverse applications of bio-nanomaterials in environmental contexts, including pollution detection, remediation, and sustainable resource management. It shows the multifaceted role of bionanotechnology in addressing environmental challenges.

minimizing harm to the environment. Bionanotechnology emerges as a pivotal player in this endeavor, harnessing nanoscale materials for diverse applications such as biosensors for pollutant detection in air, water, and soil, bioremediation techniques, and wastewater treatment (Figure 1.4). The distinctive design, synthesis methods, and tailored modifications of materials empower them to unlock their full potential in addressing environmental challenges [172]. Advancements in catalysis and material sciences have enabled precise understanding and controlled synthesis of bio-nanomaterials, fostering their application in environmental contexts. These tailored materials exhibit unique properties, such as high catalytic activity and pollutant adsorption capabilities, making them invaluable for environmental remediation and pollution control. Bio-nanomaterials are increasingly integrated into various environmental technologies, offering innovative solutions for wastewater treatment, air purification, and sustainable energy production, thus contributing to a greener and more sustainable future (Figure 1.4). The depletion and contamination of freshwater sources have become significant concerns due to anthropogenic activities. Inorganic pollutants, though naturally occurring, have increased in concentration due to human influence, posing health risks such as cancer and neurodegenerative diseases upon accumulation in the body. Organic pollutants, primarily from surface runoff, industrial discharge, and agricultural practices, pose a persistent threat as they easily accumulate in biological systems. Addressing these pollutants is crucial for safeguarding global human health and preserving freshwater resources [173]. Indeed, wastewater treatment is increasingly vital to meet growing demands for freshwater. With water scarcity becoming a pressing global issue, the conversion of wastewater into a reusable form is essential for sustainable water management. Implementing efficient wastewater treatment

processes not only helps alleviate water shortages but also mitigates environmental pollution and reduces the burden on natural water sources. As populations expand and industrial activities intensify, the urgency to develop and deploy effective wastewater treatment technologies becomes paramount to ensure a reliable and safe water supply for future generations.

1.4.4.1 Role of Bio-nanomaterials in Water Remediation

Bio-nanomaterials play a pivotal role in combatting water pollution challenges, offering innovative solutions across detection, remediation, and monitoring domains. The nanobioremediation approach presents a versatile and cost-effective solution with minimal environmental impact for addressing various pollution challenges. This approach holds promise for a diverse range of applications, spanning the treatment of groundwater and wastewater, remediation of heavy metals and hydrocarbons, and restoration of polluted soil sediments. By harnessing innovative techniques and technologies, such as advanced filtration, biological processes, and chemical treatments, we can effectively address various contaminants and pollutants present in environmental matrices. This multifaceted approach not only helps safeguard water resources but also promotes the revitalization of ecosystems and protects human health from the adverse effects of pollution [174]. Further, the efficacy of nanobioremediation in treating contaminated water sources has been demonstrated, showing its potential to mitigate pollutants while minimizing adverse effects on the environment [175]. Furthermore, studies have shed light on the effectiveness of nanobioremediation techniques in addressing heavy metal contamination, offering promising avenues for remediation efforts in industrial settings [176]. Overall, the nanobioremediation approach emerges as a promising strategy for addressing diverse pollution challenges, offering sustainable solutions with broad-ranging applications and minimal ecological damages.

Detection and Monitoring: Bio-nanomaterials, including NPs and nanocomposites, play pivotal roles in biosensor development for detecting water pollutants. By functionalizing these nanomaterials with biomolecules, their sensitivity and selectivity are heightened, facilitating precise identification of targeted pollutants in water samples. Nanomaterial-based sensors enable real-time monitoring of diverse water quality parameters, including heavy metals, organic pollutants, and pathogens. This integration of advanced nanotechnology with biosensing offers a potent toolset for ensuring water safety and environmental health through rapid and accurate pollutant detection and monitoring [177]. Advanced techniques such as nanoscale sensors and imaging afford rapid and accurate analysis of water samples, aiding in the timely identification and monitoring of pollutants.

Water Treatment and Remediation: Bio-nanomaterials with expansive surface areas, such as activated carbon NPs or nanocomposites, are pivotal in purifying water by adsorbing pollutants. Advanced oxidation processes leverage nanocatalysts to efficiently degrade organic contaminants, rendering them less harmful. Water filtration systems incorporate bio-nanomaterial-based membranes, such as carbon nanotubes and graphene oxide, for effective contaminant and pathogen

removal. Chemical precipitation and reductive dechlorination employ nano zero-valent iron (nZVI) NPs to diminish organic pollutants and heavy metals. In photocatalytic water treatment, nanomaterials such as titanium dioxide NPs degrade contaminants upon light exposure. Engineered microbial NPs, such as magnetotactic bacteria or alginate-encapsulated microorganisms, play roles in targeted pollutant removal, bolstering comprehensive remediation strategies. These diverse applications underscore the versatility and efficacy of bio-nanomaterials in addressing water pollution challenges [178].

1.5 Advantages of Bio-nanomaterials

1.5.1 Enhanced Adsorption Capacities

Bio-nanomaterials often have a high surface area, which offers more active adsorption sites for pollutants. Further, bio-nanomaterials can have their surface changed or functionalized with particular groups to improve the effectiveness and selectivity of adsorption for pollutants of interest. *Natural predilection for Pollutants*: Some bio-nanomaterials that come from natural sources could have an innate affinity for particular pollutants, which would make them useful adsorbents for such pollutants [179]. Because many bio-nanomaterials decompose naturally, the long-term environmental effect is reduced and issues with adsorbent persistence are resolved. The quality of biocompatibility is ecosystem-safe, because bio-nanomaterials are frequently biocompatible and provide less hazards to ecosystems, and they can be used in environmental applications without endangering plants, animals, or microorganisms. *Selective Adsorption Targeted Removal*: Bio-nanomaterials can be engineered to selectively adsorb specific contaminants, allowing for targeted removal of pollutants from complex mixtures [180]. *Synergistic Effects Composite Materials*: Bio-nanomaterials can be combined with other materials to form composite structures with enhanced adsorption capacities, benefiting from synergistic effects. *Renewable Resources Sustainability*: Since many bio-nanomaterials are made from renewable resources, they support sustainability objectives and lessen reliance on nonrenewable resources. *Simplicity of Synthesis Flexible Manufacturing*: Large-scale environmental remediation initiatives can benefit from the varied manufacturing and scalability of bio-nanomaterials, which can be produced using environment-friendly and economically viable ways [181]. *Adaptive Conduct Materials That Respond to Stimuli*: Certain bio-nanomaterials have responsive properties, including being sensitive to changes in pH or temperature, which can lead to the controlled release and recovery of contaminants that have been adsorbed [182].

1.5.2 Potential for Microbial Synergy

The use of bio-nanomaterials in conjunction with microorganisms can lead to microbial synergy, where the combined effects of the materials and microbes result in enhanced performance or new functionalities. This synergy can offer

several advantages in various applications. Bio-nanomaterials can enhance the bioavailability of nutrients and trace elements for microorganisms, promoting their growth and activity. Nanostructures of bio-nanomaterials can provide a high surface area, offering more attachment sites for microbial colonization and biofilm formation [183, 184].

Bio-nanomaterials can be functionalized to selectively activate specific microbial strains, promoting the growth of beneficial microorganisms while inhibiting harmful ones. Bio-nanomaterials can encapsulate microorganisms, providing protection against harsh environmental conditions and facilitating their delivery to target sites. Bio-nanomaterials can contribute to the stabilization of microorganisms during storage and transportation, ensuring their viability for applications. Bio-nanomaterials can serve as carriers for the controlled release of microbial products, such as enzymes or antimicrobial compounds, enhancing their effectiveness [185].

1.5.3 Sustainable Sourcing and Production

1.5.3.1 Environment-Friendly Production Methods

Environment-friendly production methods of bio-nanomaterials involve processes that minimize environmental impact, use sustainable resources, and adhere to green chemistry principles. These methods aim to reduce energy consumption, waste generation, and the use of hazardous chemicals.

Green Synthesis: Utilize biological organisms such as bacteria, fungi, plants, or algae to synthesize nanomaterials. This method often involves the reduction of metal ions to form NPs, and it eliminates the need for harsh chemicals. Use plant extracts, fruit juices, or other natural extracts as reducing and stabilizing agents for the synthesis of NPs. These extracts contain bioactive compounds that facilitate the reduction process [186].

Silver NPs biosynthesized using plant extracts, such as those from Aloe vera or green tea, contain bioactive compounds that act as reducing and stabilizing agents. These extracts are mixed with metal precursors to produce silver NPs [187].

Microwave and Ultrasonication: Apply microwave or ultrasonication-assisted synthesis methods to reduce reaction times and energy consumption during the production of bio-nanomaterials [188].

Solar-Assisted Synthesis (Photocatalysis): Use solar energy as a driving force for bio-nanoparticle synthesis. Photocatalytic reactions can be employed with sunlight, reducing the reliance on conventional energy sources. Zinc oxide NPs can be synthesized using sunlight as a catalyst. Photocatalysis harnesses solar energy to drive the NP synthesis process [189].

Biosurfactant-Assisted Synthesis: Incorporate biosurfactants produced by microorganisms as stabilizing agents in the synthesis process. This reduces the reliance on synthetic surfactants [190]. Biosurfactant-mediated synthesis of iron oxide NP and microbial-derived biosurfactants are used as stabilizing agents in the synthesis of iron oxide NPs. This approach eliminates the need for synthetic surfactants [191].

1.6 Current Challenges and Future Prospects

1.6.1 Toxicological Concerns

Bio-nanomaterials have a lot of potential for environmental cleanup by enabling recycling, lowering energy consumption throughout the manufacturing and production processes, and creating and utilizing environmentally benign material. However, their application may raise toxicological issues. There exists a potential risk of bio-nanomaterials accumulating in organisms and inadvertently entering the food chain, which could have far-reaching implications for ecosystem health and human well-being. Therefore, it is imperative to conduct thorough research on the fate, behavior, and toxicity of these materials in various environmental compartments to assess their potential impacts accurately. Implementing robust risk assessment frameworks and regulatory measures can help mitigate potential adverse effects and ensure the sustainable application of bio-nanomaterials in environmental remediation practices. By proactively addressing these challenges, we can harness the benefits of bio-nanomaterials while minimizing their potential risks, thus advancing toward a more sustainable and resilient environment [192]. The bioaccumulation of bio-nanomaterials at higher trophic levels may result in biomagnification, increasing concentrations and potential toxicity. Bio-nanomaterials may affect microbial communities crucial for environmental processes, leading to disruptions in nutrient cycling and soil health [193]. Some bio-nanomaterials with antimicrobial properties may contribute to the development of antibiotic resistance in microorganisms. During the lifecycle of bio-nanomaterials, there is a potential for the release of toxic components or breakdown products, which may pose risks to the environment [194].

The release of bio-nanomaterials into aquatic environments poses risks to aquatic life, disrupting ecosystems by affecting behavior and physiology of organisms. Changes in feeding patterns, reproduction rates, and growth can occur, necessitating thorough risk assessments and stringent regulations to mitigate adverse effects. Prioritizing environmental stewardship and precautionary measures are essential for safeguarding aquatic biodiversity and promoting sustainable coexistence with bio-nanomaterials. Workers involved in the production or application of bio-nanomaterials may face occupational exposure, leading to potential health risks [195]. The presence of bio-nanomaterials in consumer products or the environment may result in unintended human exposure. The environmental fate and persistence of bio-nanomaterials raise concerns about prolonged exposure and potential cumulative effects. It is crucial to assess their long-term impacts on ecosystems and human health, emphasizing proactive monitoring and stringent regulation to mitigate risks effectively. The mobility of bio-nanomaterials within ecosystems may influence their distribution and impact on different environmental compartments. Current regulatory frameworks may not have standardized testing protocols for assessing the environmental fate and toxicity of bio-nanomaterials, posing challenges in risk assessment [196].

The unintended effects of bio-nanomaterials on nontarget organisms may lead to ecological imbalances and biodiversity loss. Bio-nanomaterials may modulate immune responses in organisms, potentially leading to immunotoxic effects. The

ethical implications of introducing engineered bio-nanomaterials into natural ecosystems, including the potential for unintended consequences, should be carefully considered [197].

1.6.2 Scalability and Commercial Viability

Several challenges and opportunities need to be considered when assessing the feasibility of scaling up the production and commercialization of bio-nanomaterials for environmental applications. Many bio-nanomaterials are produced through biological synthesis methods, which may pose challenges in terms of scalability compared to conventional chemical synthesis routes. Ensuring consistent quality and properties of bio-nanomaterials at a large scale can be challenging due to variations in biological processes and raw material sources. The cost of producing bio-nanomaterials at scale must be competitive with alternative technologies and materials to attract commercial interest [198].

Adhering to regulatory requirements and standards becomes more complex at a larger scale, necessitating robust quality control and compliance measures. The availability of raw materials, especially if derived from natural sources, may be a limiting factor when scaling up production. Advances in bioprocessing and fermentation technologies can contribute to more efficient and scalable production methods for bio-nanomaterials. Synthetic biology techniques can be employed to design and engineer microorganisms for enhanced production of bio-nanomaterials with desired properties. Collaborative efforts and consortia involving academia, industry, and government agencies can facilitate the sharing of resources and expertise, contributing to scalable solutions. Continuous optimization of production processes, including reaction conditions and purification methods, can enhance scalability while maintaining cost-effectiveness [199].

Convincing industries and regulatory bodies of the effectiveness and safety of bio-nanomaterials can be a challenge, impacting their market acceptance. Bio-nanomaterials must compete with existing technologies and materials, and their advantages over conventional methods need to be clearly demonstrated. The need for significant initial investment in research, development, and infrastructure can be a barrier to commercial viability [200].

Bio-nanomaterials can offer tailored solutions for specific environmental remediation challenges, providing a niche market where their unique properties are advantageous. Stringent environmental regulations and growing awareness of sustainable practices create opportunities for bio-nanomaterials to meet compliance requirements. Companies adopting bio-nanomaterials for environmental remediation as part of their CSR initiatives can enhance their image and market position. Collaboration with established industries and environmental service providers can facilitate the integration of bio-nanomaterials into commercial applications [179].

1.7 Future Perspectives

In the fields of industrial technology, agriculture, medical, ecology, and others, nanobiotechnology is a rapidly growing field. Newer methods for synthesizing

biomaterials using biologically active substances or biological systems with little interference from very hazardous physicochemical processes have been made possible by advancements in research. In the quest to enhance the utility of biological NPs, a multifaceted approach will be beneficial via integration of biomolecules with various other NP types, including inorganic and polymeric materials. This integration has created new application possibilities through an array of biofunctionalization strategies. Even Nevertheless, there is still a lot of unexplored potential in the field of bio-nanomaterials.

The intrinsic stability of bio-nanomaterials presents a promising avenue for sustainable and environmentally beneficial applications (Figure 1.4), particularly in mitigating the toxicity of pollutants. However, current research suggests that while biogenic NPs offer potential in reducing microbial toxins across diverse environments, their efficacy may be limited by certain factors. To fully harness the potential of bio-nanomaterials in toxin suppression, a deeper understanding of the biochemical and molecular mechanisms underlying their interaction with toxin formation processes is imperative. This necessitates additional investigation into the intricate interplay between biogenic NPs and microbial toxins, elucidating the specific pathways and mechanisms through which they exert their mitigating effects.

Moreover, while bio-nanomaterials show promise in detecting harmful substances, there exists a pressing need for further research and development to streamline detection processes for widespread application in large-scale ex situ environments. Advancements in this area will not only facilitate the swift identification of environmental toxins but also pave the way for effective remediation strategies, thereby bolstering efforts toward environmental preservation and sustainability.

Looking forward, driven by recent technological strides and innovative approaches, the frontier of biological NPs is primed for a breakthrough. From drug delivery systems to diagnostic tools, these advanced NPs hold significant potential for applications across diverse fields. However, amidst this anticipation lies a continued journey of exploration and investigation. Researchers are tasked with uncovering the full range of capabilities inherent in these novel constructs, delving into biochemical and molecular intricacies to unlock their true potential.

With each scientific advancement, we draw closer to a future where biological NPs play an integral role in scientific and technological advancements. Thus, the journey persists – a continuous quest for understanding and innovation that will shape the trajectory of bionanotechnology for years to come.

1.8 Conclusion

Nanobiotechnology is indeed a rapidly growing field with wide-ranging applications across various sectors including environment, agriculture, medicine, and industry. In the environmental sector, nanobiotechnology is utilized for pollution remediation, water purification, and environmental monitoring. In agriculture, it contributes to crop improvement, soil health management, and pest control. In medicine, nanobiotechnology enables advancements in drug delivery, diagnostics,

imaging, and regenerative medicine. Moreover, in industry, it plays a role in materials science, electronics, energy production, and manufacturing processes. Recent advancements in research have led to innovative approaches for synthesizing biomaterials using biologically active compounds or biological systems, minimizing reliance on hazardous physicochemical processes. Monitoring different types of bio-nanomaterials and different complex conjugates has been discussed in this chapter. The bio-nanomaterial could be biological molecules of nanometer scale. There is other kind of bio-material that is derived from the biological molecules. This involves green synthesis of metal or metal oxide NPs and derived nanosized cellular components such as exosomes, outer membrane vesicles, and viruses. Bio-nanomaterials are also formed by integration of various other organic and inorganic biomolecules with the metal/metal oxide NPs. The utilization of biofabricated nanomaterials shows promise in reducing pollutant toxicity, enabling their recyclability due to their stable properties, thereby promoting eco-friendly and sustainable practices. Various available bio-nanomaterials found application in the fields of nanomedicine, drug delivery biosensor (diagnostics), bioelectronics, food industries, and water remediation. However, there still exists a gap in effectively mitigating microbial toxins using biogenic NPs, necessitating further exploration of their mechanisms of action at biochemical and molecular levels. Although biofabricated nanomaterials hold the potential for detecting specific toxic compounds, additional development is required to enable their efficient use in large-scale environmental monitoring.

With the recent developments, bio-nanomaterials could be the significant utility in the field of data storage, diagnostics, drug delivery, agriculture, and nutraceuticals.

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