

Review Article

Renewable Polysaccharide and Biomedical Application of Nanomaterials

Rahul Kanaoujiya ¹, Shruti Kumari Saroj,¹ Shekhar Srivastava,¹
and Manoj Kumar Chaudhary ²

¹*Synthetic Inorganic and Metallo-Organic Research Laboratory, Department of Chemistry, University of Allahabad, Prayagraj, India*

²*Central Department of Physics, Tribhuvan University, Kathmandu, Nepal*

Correspondence should be addressed to Rahul Kanaoujiya; rahul.k@allduniv.ac.in
and Manoj Kumar Chaudhary; manoj.chaudhary@ac.tu.edu.np

Received 15 February 2022; Revised 27 March 2022; Accepted 31 March 2022; Published 15 April 2022

Academic Editor: H C Ananda Murthy

Copyright © 2022 Rahul Kanaoujiya et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Nanotechnology being undoubtedly an uncut gem over the past few years has been in sighting as a new form of branch with its vigorous discoveries which have led to its divergent evolution giving emergence not only in the pathway of knowledge but also developing technological techniques. The constituting nanoparticles and its versatile properties with dynamic structures have made a major breakthrough in the past few years for its role in biotechnology arising nanobiotechnology, antipollution, renewable polymers, and its biomedical applications. Nanostructure composites forming nanomaterials on the basis of its working are pectin, cellulose, lignin, hyaluronic acid, bacterial cellulose, Arabic gum, and bacterial biosurfactants. In the recent years, it is seen that nanocomposites are giving promising results in medical technology incorporating with useful metal nanoparticles such as silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), diamond nanoparticles, zinc oxide (ZnO), and titanium oxide (TiO). Some useful biomedical applications are in anticancerous, sunscreen, antiageing, and antitumorous. They have shown to be nontoxic at a certain level. Nanoparticle composites have proven with right amount of doping, and experienced techniques have given excellent results. Nanofibers of biodegradable poly(L-lactide) (PLLA)/poly(lactide-co-glycolide) (PLGA) compounds are used in drug delivery, folate redox-responsive chitosan nanoparticles (FTC-NPs) also as anticancer drug delivery, and mesoporous silica nanoparticles-silver nanoparticles as a tissue growth in vivo processes. The study of a biosynthetic pathway of therapeutic drugs is still much needed. Waste management of renewable nanopolymers are an ultimate goal so that there are less haphazard elements towards the environment.

1. Introduction

As we approach to the recent times of our study with biological environment, we observe that not only it provides us with basic necessities but also classifying itself into producing different forms of nanocomposites with splendid attributes and serving many purposes. These nanocomposites aligned in the formation of polymers giving a spectrum of scope. The fact that withholds with the nanocomposite's polymers is its unique way of matrix formation constituting molecules (e.g., carbohydrates, colloids, and amino acids). The importance of these colloids is not only subjected with

the formation of it but also in regard with sustainability. Renewable polymers are the polymers composed of natural product or the tendency of it converted into simpler polymers that are unpolluting to the biological ecosystem, ceaseless resource of energy contributing a promising shelf life. The polymers from renewable resources [1] include polysaccharides, lignin, triglycerides, chitosan, and amino acids. Some other renewable resources of nanocomposites materials including fibroin of spider, silkworm's fibroin [2], and nacre mother layer [3] of mollusks have an emerging contribution towards renewable polymers; thus, these polymers owing to its sustainability possessing compact matrix

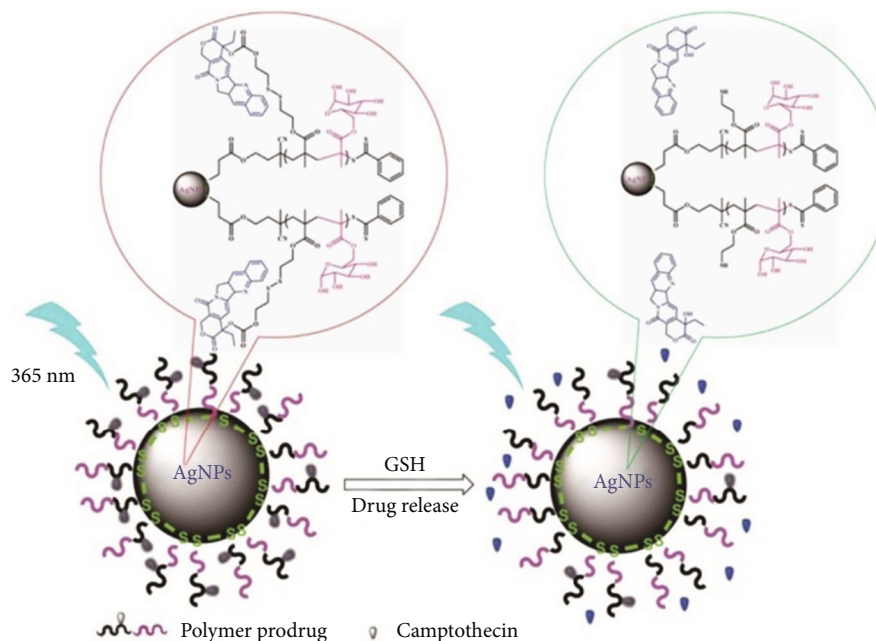


FIGURE 1: Representation of fluorescence “off” and “on” with the release of CPT from redox-responsive P(MACPTS-coMAGP) @AgNPs nanoparticles. Reproduced from [73]. Chinese Chemical Letters (Elsevier).

structure are established with other nanocomposite polymers; the following physical attributes such as interfacial tensile, layering of matrix, bonding energy, resistance under pressure, elasticity, and fabrication are considered. In terms of chemical versatility of nanostructure composites of the renewable polymers, we see the 1D, 2D, and 3D [4] forms and wavelength of electrons and photons [5], mitigating damages at nanoscale level, stability, redox properties [6], optical activity, and crystallinity [7]. On analyzing the physical and chemical versatility of the following nanocomposite particles with technology and advanced resources, this can be crafted by engineers and aid in the rapid production of quality in the polymers. The metallic catalyzed nanoparticle has its own different functions with respect to its contributing strategic properties. Some metallic catalyzed nanoparticles are titanium (II) oxide (TiO) [8], zinc oxides (ZnO), silica, iron oxides (Fe₂O₃), silver nanoparticles (AgNPs) [9], gold nanoparticles (AuNPs) [10], diamond nanoparticles [11], and noble nanostructured particles [12]. Zinc oxide (ZnO) and titanium oxide (TiO) are known to be manufactured worldwide with a contribution of 10,000 tons annually. Zinc oxide (ZnO) and titanium oxide (TiO) own a photocatalytic attribute of cosmetics in sunscreen. Silver nanoparticles (AgNPs) display the ability to cease microbes making it a prerequisite quality for packaging (Figure 1). Gold nanoparticle (AuNPs) and its nanoscale reduce ageing and help as an elixir of anti-inflammatory with blood circulation. Iron oxide (Fe₂O₃) [13] nanoparticles are showcased as an acceptable food colorant, and lastly, diamond nanoparticles with antioxidizing and nontoxic levels with other nanocomposites enact as shielding agent against UV and oxidation. During last year, major power cuts were observed all claiming to the shortages of fossil resources (coals, crude oils, etc.)

and hikes in oil prices and commodity goods. Increasing unlimited demand of consumption goods and other vital resources is leading to scarcity of resources which are set to be depleted in some years about time. There is a need to combat with such crisis; thus, the vigorous conversion of biomass materials into chemical materials has led to an increasing demand in companies. This major breakthrough from the past few years has not limited with an idea of consumption, but with abroad spectrum in urge of biorefineries with less wastage, materials are being mandated but execution is slow. During the esterification of glycerol with fatty acids from plant oils of triglycerides [14] containing other modification that led to increasing chances of new nanostructured materials as shown in (Figure 2), this promising nanostructure from such plant-based oils is manifested in proving with different possibilities of matrices and functions. They are not exclusively in narrow fundamental consumption but a breakthrough of other applications too.

We see that the polysaccharide are subdivided into three nanomolecular structure in order to give the desired result that was accomplished by interaction of two opposite charge form, i.e., anionic and cationic polymer (Figure 2); to form a polyelectrolyte complex, the amphiphilic polysaccharide orients themselves to accomplish emulsions, and the addition of crosslinkers unites into ionotropic gelation per its activating function. Some drawbacks reported are seen that all renewable polymers are not guaranteed biodegradable polymers even despite having biological nanocomposites. Secondly, there is not much improvisation with the transportation to the target receptors or a pathway that has been developed to transport the nanostructured polymers. In this article, we will not be discussing much of microstructured particles.

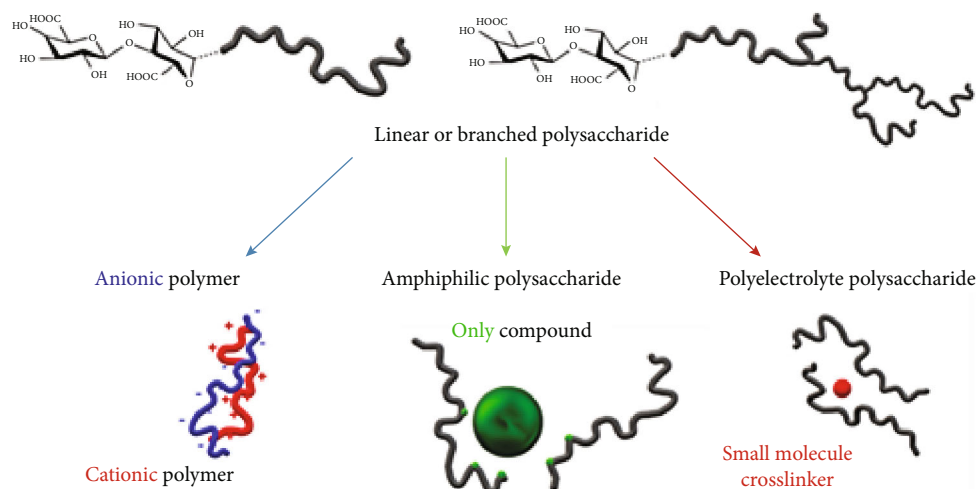


FIGURE 2: Diagrammatic representation of formation of polysaccharide-based nanostructures. Reproduced from [15]. Copyright2020, Molecules (MDPI).

2. Historical Review of Nanostructure Polymeric Material

Humans have previously utilized the natural concrete nanofibers more than 4500 years a long time ago. Based with the synthetic chemical process, the ancient Egyptians also used nanomaterials besides than 4000 years ago [16]. The synthesized approximately ≈ 5 nm diameter PbS nanoparticles were used in hair dye [17]. In the 3rd century, Egyptians used sintered mixture nanometer-sized glass and also in quartz; the “Egyptian blue” was the first synthetic pigment first used and prepared by the Egyptians [18]. Egyptian blue constitutes a mixture of $\text{CaCuSi}_4\text{O}_{10}$ and SiO_2 , i.e., mixture of glass and quartz. On the basis of archaeological explorations, the Egyptian blue used for decorative purposes has been observed in the ancient period in the region of Mesopotamia, Egypt, and Greece. In the scientific arena, Michael Faraday scientifically first described nanoparticle preparation and also initiated the history of nanomaterials in the year 1857. He also give out that the optical features of gold colloids, i.e., Au, are differing compared to their bulk. In the year 1908, Mie explored that the metal colloids have a specific color, the reason behind their quantum size effects. SiO_2 nanoparticles were manufactured as derivative to carbon black for rubber strengthening in the year 1940s. Nowadays, manufactured nanomaterials can significantly enhance the features of bulk materials inside their conductivity, lightness, durability, and strength, and they can give a very useful features such as antifreezing, antibacterial, self-healing, and self-cleaning. In the medieval period, it was found that the red- and yellow-colored stained glass was produced by Au and Ag nanoparticles approximately [19]. In the 9th century, Mesopotamians started using ceramics for metallic luster ornament [20]. In the 19th century, a famous Satsuma glass in Japan was produced. The adsorption properties of Cu nanoparticles are improved by brightening Satsuma glass with ruby color [21]. In the 5000 BC, clay was frequently used to bleach wools and cyprus in cloth [22]. Samsung introduced an antibacterial technology based on

Ag nanoparticle they used in air purifiers, vacuum cleaners, washing machines, refrigerators, and air conditioners, studied in the year 2003 [23]. Nanoparticles are considerably used in the production such as transparent layers used for heated fillers in tires to enhance adhesion on the road and improve the stiffness and window panes [24]. Mercedes-Benz studies a series of production for both type of metallic and nonmetallic paint finishes studies in the year 2003. TiO_2 nanoparticles are used in dye sensitization ability and in solar cells. In the year 2012, Summer represents the first major commercial use of dye-sensitized solar cells [25]. A series of product approximately 1814 nanotechnology-based consumer products are commercially accessible in over 21 countries.

3. Nanostructured Natural Renewable Polymers

3.1. Polysaccharide. Polysaccharide is one of the most versatile and foremost compounds in the biological nature. Polysaccharide is in an abundant quantity and cosmopolitan. Polysaccharide is one of the emerging nanocomposite polymers and highly in demand than the synthetic polymers. Their versatility is in terms of medical, industrial, economic, cosmetic, and recreational activities; thus, with this trait, they are harmonically aligned with the biological systematic resulting in a biodegradable resource. These nanostructured polymers are not only a good biodegradable resource but also in developing an eco-friendly performance. On studying the structural figure of the polysaccharide compounds, we see interlinking functional groups that have a capacity of forming noncovalent bonds with living and nonliving tissues with its carboxyl, hydroxyl, and amino groups. This compact raw structure of polysaccharides is being essentially involved in the production of pure chemical substances for, e.g., polyaddition of bioethanol for ethylene glycol. When other polysaccharides come into contact with hydrophobic and hydrophilic parts, the insertion of polar groups towards the hydrophobic part can result in a glucose backbone arrangement, which may boost the amphiphilic character of the

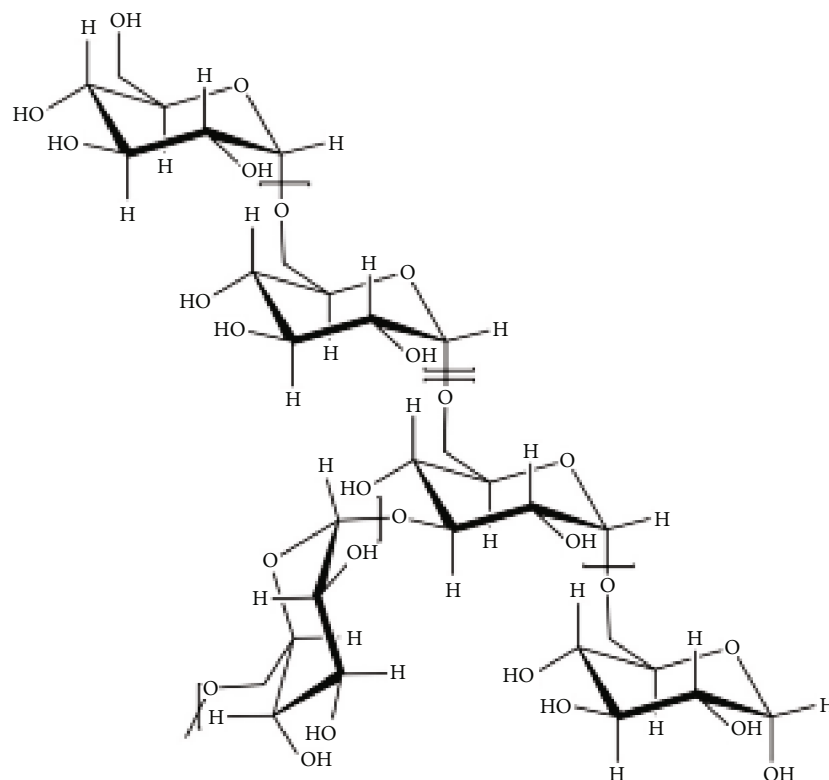


FIGURE 3: Schematic representation of dextran as an example of a branched polysaccharide. Reproduced from [33]. Copyright 2014, Frontiers in Chemistry.

polysaccharide [26]. With the introduction of a polar group through esterification in the polysaccharide nanocomposites, it has expressed the hydroxyl groups [27]. With this process, it has led to the improvement of polysaccharides with the modular structure of cellulose and its derivatives [28, 29] as in cellulose ethers (methylcellulose, carboxymethyl cellulose, and hydroxypropyl cellulose) [30]. They have been a promising nanocomposite for the industrial, medical, cosmetic (shampoos and toothpastes), and lastly edibles (gelato manufacturing).

3.2. Lignin. Lignin nanocomposites are considered being in a profound aggregate in nature. In recent years, lignin, the second most prevalent biopolymer after cellulose, has attracted a lot of attention. Every year, it is predicted that around 21011 tons of lignocellulosic biomass wastes are generated worldwide, making lignin a readily available renewable phenolic component. It has the potential to assist the shift from a fossil-based to a biobased economy by supplanting synthetic chemicals now generated from fossil resources because it is already produced in side streams of pulp and biorefineries. Because only around 40% of the lignin generated in pulping processes is required to meet the processes' internal energy requirement, there is the potential to greatly increase the quantity of lignin (Figure 3) used for material purposes, while still maximizing the efficiency of all biomass components should be expanding in terms of sustainability. Plants are a major component for lignin about 15-30% of its biomass apart from cellulose. So not only it is a considerable material for the paper and cardboard industry but it also

provides a poor solvation rate with respect to aqueous solution; this is because of its lignin composition matrix. Dextran (Figure 3) was originally derived from wine. Lignin has a highly branched polyphenolic polyether comprising of three structural monomers of 4 hydroxyl phenyl guanylyl and syringyl (Figure 3) derivatives chained with the aromatic and aliphatic ether with hyper branches (Figure 3) [31, 32].

Lignin nanocomposites (Figure 3) are considered being in a profound aggregate in nature. Plants are a major component for lignin about 15-30% of its biomass apart from cellulose. So not only it is a considerable material for the paper and cardboard industry but it also provides a poor solvation rate with respect to aqueous solution; this is because of its lignin composition matrix. Lignin (Figure 3) has a highly branched polyphenolic polyether comprising of three structural monomers of 4 hydroxyl phenyl guanylyl and syringyl derivatives chained with the aromatic and aliphatic ether with hyper branches. It is an asymmetric matrix with 2% of lignosulphonate seen in promoters of adhering in material allowing industrial manufacturers in making of bricks, ceramics, fodder pods for livestock, pavement materials, and most importantly circulation of oil-seizing platforms. Since lignin is an asymmetric compound, it was found that with phenolic and aliphatic compounds on further characterization using carbon nanotubes (2,4 toluene diisocyanate), TDI tailed with polymer of propylene glycol functions as chemical sensors.

Further, the hydroxyl groups of lignin films were altered with poly(N-iso-propyl acrylamide) on using this technique

of atom transfer radical polymerization (ATRP) in a bathed environment resulting in ion-sensing nanofibers [34]. In order of carrying hydrophilic substances in lignin nanostructured containers, it was observed with the creation of a hollow nanocapsules by forming a boundary with polyaddition of lignin with TDI in reverse processing in minute emulsion and carrying with dissolving the lignin derivative in an organic solvent and water giving rise to a biodegradable lignin nanocontainer which are able to transport hydrophilic compound.

3.3. Pectin. This is the first most studied and investigated polysaccharide. It is found mainly in the cell wall and middle lamellae of some herbaceous plants such as the peels of citrus fruits like lemon, kumquats, peels of apple pomace, sunflower depurating, and stems of broccoli, thus producing white to light brown-colored powder. Pectin is a heteropolysaccharide constructed polymer of galacturonic acid and rhamnose as its spine with connecting links with arabinose, fucose, galactose, and xylose. This is a structural heteropolysaccharide having a main component composed of α -D galacturonic acid and other sugar acids like D-galactose and L arabinose residues [35]. The contributing characteristics of nanoparticle size of pectin have degree of esterification, methoxylation, and pH levels; it can be detected in the diverse range of ~50 nm-850 nm. Pectin can be studied on the basis of size, shape, and biocompatibility ensuing in three reasonable classifications based on methoxylation of pectin as high methoxylated pectin (HMP), low methoxylated pectin (LMP), and amidated methoxy pectin (AMP). High methoxylated pectin (HMP) having a degree of esterification smaller than 50% and low methoxylated pectin (LMP) having a degree of esterification greater than 50%. When HMP is deesterified using ammonium ions, low methoxylated amidated pectin (AMP) is formed having a DE greater than 25%. Due to its strong mucoadhesiveness, gelling capability, and solubility in many pectin, nanoparticles (NPs) are used in wound healing and oral medication administration natural settings. As a counter to metallic nanoparticles, Birch and Schiffman produced self-assembled polyelectrolyte complex nanoparticles comprised of chitosan and pectin for the treatment of persistent wounds caused by different lifestyle conditions. Antibacterial, anti-inflammatory, and preferred stability in pH ranges of 3.5 to 6.0 are provided by bioadhesive and biodegradable polymeric nanoparticles such as chitosan and pectin NPs, implying significant future potential in wound healing.

It is considered to be a natural diet for human beings but still insignificant with its nutritional amount. Isolated pectin is found to have 30% of polysaccharide in them. Pectin uniquely characterized with a thick gel like appearances is mainly used in confectionaries such as jams, gelato, preservative, and conserves on adding to concentrated solution. Since pectin's resource comes mainly from citrus, their nanostructures are packed with vitamin C which is one most crucial effective in the cosmetic industry. Heavy metal toxicity, which can be caused by exposure to lead, mercury, arsenic, and other elements, has also been treated with pectin. Some individuals feel that modified citrus pectin (MCP)

might aid in the excretion of harmful chemicals from the body. However, there is a scarcity of neutral research to back up such conclusions. Furthermore, due to pectin's strong mucoadhesive nature, all three citrus pectin specimens showed similarities in their description investigations, and we believe they are excellent carriers for oral administration of hydrophobic drugs in regulated dose forms. We aim to conduct comprehensive drug delivery research in the near future using the created and well-characterized pectin nanoparticles. Pectin is indigestible to humans in its native condition. The nanostructure composite of pectin is isolated from the technique of nanoemulsions that can prepare an aqueous gel of sodium caseinate forming a multifunctional complex electrolyte loaded with curcumin extract [36]; its unique compact nanocomposite matrix has been a favorable model for shampoos and lotions.

3.4. Arabic Gum. Arabic gum comes from the *Acacia senegal* and *Acacia seyal* trees that are found in the desert regions. The Acacia tree is most commonly grown in water scarce region and hot climate of African region. The productive extraction of the nanopolymer gum resin is dependent with the season, harvest time, life span of the tree, and most importantly with the quality condition of the tree. The origin of Arabic gum has been found to be one of the ancient times dating back to 2650 BC as due to their viscous nature, they were considered to be utilized in mummification of dead bodies and prime source to protect food from decay. The Arabic gum (Figure 4) nanobiopolymers consist of a cocktail of carbohydrates (mainly D galactose and L arabinose unit) (Figure 4) [37] and proteins (arabinogalactan protein complex (AGP), arabinogalactan, and glycoprotein) (Figure 4) [38]. The dual nature of Arabic gum both being hydrophilic and hydrophobic has made it suitable for easily altering food tastes with shielding and long-lasting amalgamative in food quality products. Other source of Arabic gum such as xanthan, gaur, and locust bean is being explored [39].

Likewise, the adsorbents' exceptional regeneration and recovery of the adsorbed species indicated that it may be used for water filtration. The nanocomposite's superparamagnetic nature, thermal stability, large surface area, and porous structure made it a one-of-a-kind material for wastewater treatment applications. Arabic gum possesses several biological characteristics as an antioxidant in lipid metabolism and in the treatment of a variety of disorders, including diseases of the kidneys, the heart, and the gastrointestinal tract. Arabic gum is used in confectionery, bakery, dairy, and beverage and as a preservative in the food sector. A microencapsulating agent is a substance that may be used to encapsulate. It is used as a stabilizer in dairy products. Because Arabic gum contains a variety of amino acids, it boosts antioxidant capability. Lysine, tyrosine, and histidine are typically considered acid residues as biomolecules that act as antioxidants.

The biological features include antioxidant qualities, an influence of Arabic gum on renal function, blood glucose concentration, intestinal absorption, Arabic gum breakdown in the gut, lipid metabolism, tooth mineralization, and hepatic macrophages, among others. Because Arabic gum

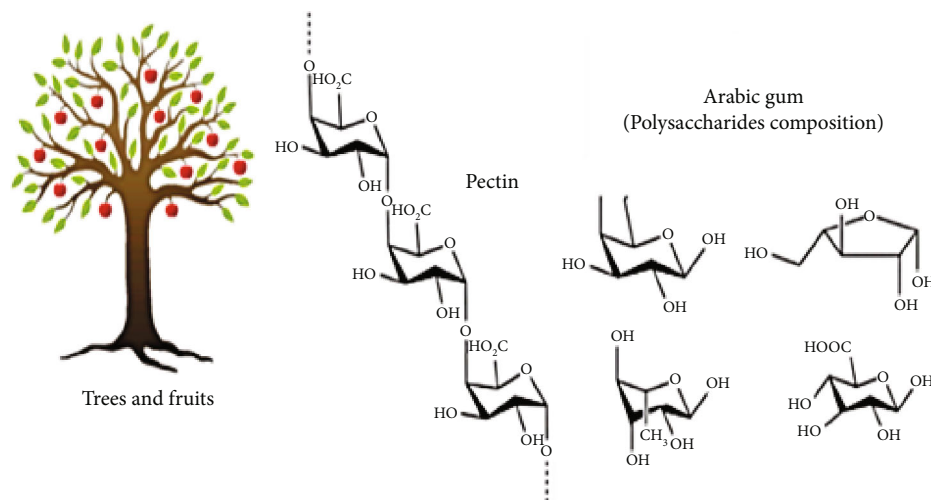


FIGURE 4: Schematic representation of chemical structure of Arabic gum. Reproduced from [15]. Copyright2020, Molecules (MDPI).

contains a variety of amino acids, it boosts antioxidant capability. Arabic gum affects renal function via lowering blood pressure and reducing concentration levels of creatinine and urea nitrogen in diabetic nephropathy patients. Arabic gum leads an effect on fasting blood glucose levels, and glycosylated hemoglobin levels were both considerably lower: HbA_{1c} as well as a considerable drop in blood pressure and HbA_{1c} as well as a considerable decrease in blood uric acid and total protein levels. The transport of water and electrolytes from the intestinal lumen to the bloodstream is facilitated by Arabic gum. Intestinal bacteria may convert Arabic gum to propionate, a short-chain fatty acid. Arabic gum is rich in fiber that aids in weight loss and fat deposition. Arabic gum is employed as a medication carrier in the pharmaceutical sector since it is nontoxic.

It is thought to be a biologically innocuous chemical. Arabic gum possesses several biological characteristics as an antioxidant in lipid metabolism and in the treatment of a variety of disorders, including diseases of the kidneys, the heart, and the gastrointestinal tract.

3.5. Starch. This nanopolymer composite mainly is a store house of energy for plants. The nanocomposites matrix structure comprise of linear poly(1,4- α -D-glucopyranose) with branches of (1,6- α -D-glucopyranose) (amylopectin) (Figure 5) [40]. Starch is a heteropolysaccharide made up of two types of macromolecules: linear amylose (which makes up around 10–30% of the granule) and branching amylopectin (which makes up the remaining 70–90% of the granule). Amylose (Figure 5) is a linear polysaccharide chain made up of d-glucose units joined by a (1,4)-glycosidic bond with a polymer degree varying from 300 to 10,000. Amylopectin (Figure 5) is a high-molecular-weight polymer having an amylose spine that is connected together with -(1,6) glycosidic linkages. The nanostructured composites of starch are mainly obtained by conditioning the granules using ultrasonication which has been one of the utmost factors for substituting with the fat or oil in edible oils. As emulsion stabilizers, fat replacers, flexible films, carriers of bioactive compounds, drug delivery, and adsorbents in sew-

age treatment or wastewater treatment, starch-based nanocomposites have a wide range of applications in food and agriculture, packaging, biomedical, and environmental remediation. Starch nanoparticles have an active surface area of more than 300 nm and are typically less than 300 nm in size. Starch nanoparticles, starch nanospheres, starch micelles, starch vesicles, starch nanogels, and starch nanofibers are examples of starch-based nanoparticles. Because of its renewability, biodegradability, availability, eco-friendliness, cheap cost, nontoxicity, high adsorptive capabilities, amenability to numerous chemical changes, and cohesive film-forming abilities, starch has received much interest. Through the functional (hydroxyl) groups on the starch structure, starch molecules can bond with heavy metal ions or pollutants. Secondly, starch with a high amylopectin concentration exhibits strong swelling capabilities, which are crucial in sorption applications. Carbohydrates have been utilized as reducing, stabilizing, and/or complexing agents in the majority of reported studies. Due to the interactions between the individual constituents, starch-based hybrid materials show a range of capabilities and/or novel properties, most of which are associated with synergetic effects, and have been observed in environmental remediation applications. Several starch-based composites have been found to have a strong adsorption ability for heavy metals and dyes removal. Since starch comes from a polysaccharide derivative, thus it is one of the governing factors for its versatility. However, starch in its pure or natural form has disadvantages such as poor processability, high brittleness, retrogradability, high viscosity, low adsorption capacity, and increased hydrophilicity or high water absorption capacity, which restricts its numerous environmental uses. Starch is transformed physically (hydrothermal processing (i.e. gelatinization)) or chemically (etherification, esterification, crosslinking, grafting, oxidation, and enzymatic hydrolysis) or a combination of these two processes to overcome this challenge and generate water-insoluble polymers. Polysaccharides include several reactive hydroxyl groups that can be used for direct esterification, etherification, and other chemical changes. This replacement has brought with the manageable industrial wastes. These materials offer a realistic

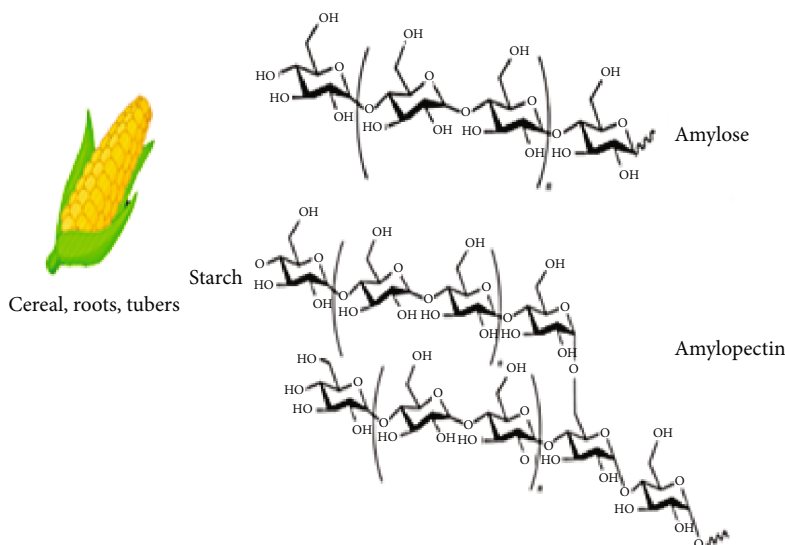


FIGURE 5: Schematic representation of chemical structure Amylose & Amylopectin. Reproduced from [15]. Copyright 2020, Molecules (MDPI).

and cost-effective alternative to petroleum-based counterparts in the fight against pollution. To eliminate different harmful impurities such as heavy metals, organic contaminants, and dye wastewater, starches are combined with metal NPs, metal oxide NPs, zero-valent metals, CNTs, and other polymers as reducing, stabilizing, and/or complexing agents. In African countries, starch meals are one of their food resources in order to combat with hunger, but still, this polysaccharide nanocomposite derivative is in the need of advancement due to their lesser number of calories provided as compared to other food resources.

3.6. Bacterial Cellulose. Bacterial cellulose is one of the natural biopolymers. It withholds a unique structure of nanofiber which are three-dimensional reticulated network matrix. In 1883, Brown discovered in *Acetobacter xylinum* and *Glucanacetobacter xylinus* aerobic conditions thriving in glucose as carbon source. Bacterial cellulose can also be extracted from *Agrobacterium* and *Sarcinia ventriculi*. Because of its nanofibrillar matrix, bacterial cellulose is very biodegradable and has excellent physicochemical qualities. Because of the high level of natural purity, this substance demonstrates negligible toxicity in practically all applications, allowing this dressing to be used directly. However, fungi, seaweed, and some bacterial species may produce cellulose, most notably the non-pathogenic, strictly aerobic, Gram-negative bacterium *Komagateibacter* sp. (previously *Acetobacter* and *Glucanacetobacter*), with *Komagateibacter xylinus* being the best researched species (*K. xylinus*). Bacterial cellulose has features that are consistent in integrating macromolecular and surface properties, which are important for clinical field both in vivo and in vitro. Bacterial cellulose has since been proven to be a promising new biomaterial for biomedical use. As a result, the objective of this review is to summarize and evaluate the most recent advancements and uses of bacterial cellulose in a biomedical environment, including the bioengineered material and bacterial cellulose.

Bacterial cellulose is at the forefront of regenerative medicine, since it improves cellular adhesion, stimulates cell proliferation, migration, and eventual differentiation, and therefore speeds wound healing. Biomedical devices built of bacterial cellulose have several advantages, including minimal toxicity and the capacity to keep wounds wet. The bacteria begin the manufacture of cellulose by passively collecting glucose from the environment, which is subsequently isomerized from glucose-6-phosphate to glucose-1-phosphate. The uridine diphosphate glucose, UDP-glucose, is formed when this isomer interacts with uridine-5-triphosphate (UTP). This UTP-glucose is subsequently converted into linear 1,4 glucan chains by cellulose synthase A, which is triggered by cyclic-di-GMP. The cellulose chains are subsequently expelled by the bacteria through holes in the cell wall. If the bacteria run out of glucose, it will switch to the fructose pathway, which uses the same biochemical pathways as the glucose pathway. A particular operon termed bacterial cellulose synthesis ABCD (bcsABCD) that was discovered in *K. xylinus* in 1999 modulates the metabolic pathways. The first gene in the bcsABCD operon, bcsA, is responsible for encoding cellulose synthase, the enzyme's catalytic component. The second gene, bcsB, is responsible for the creation of a regulatory component located on cellulose synthase that binds to c-di-GMP, which is very important since this contact promotes the formation of cellulose. The activities of bcsC and bcsD remain unknown; however, it is thought that bcsC plays a role in the formation of holes in the cell membrane, and the proteins encoded by these genes are comparable to pore-forming proteins. *K. xylinus* may grow in shallow containers with semidefined growth media in a static incubator at 30°C for 7 to 14 days, after which a thick pellicle of cellulose develops at the liquid surface contact and is readily collected. Although this is the most common technique of manufacturing BC, it has some drawbacks, including cultivation time and expense. Furthermore, since the organisms are exposed to different growth

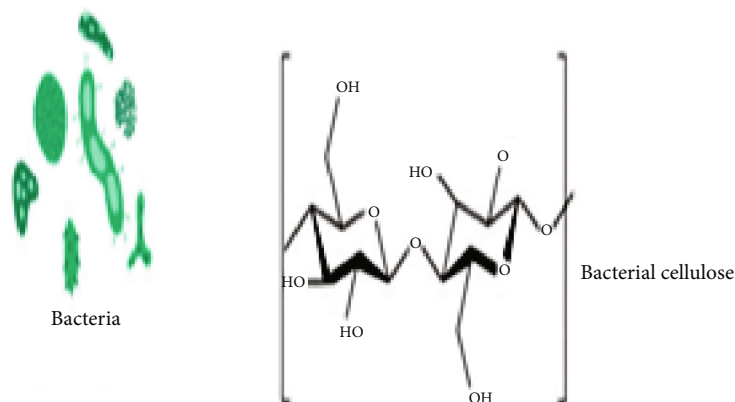


FIGURE 6: Schematic representation of chemical structure of Bacterial Cellulose. Reproduced from [15]. Copyright 2020, Molecules (MDPI).

environments, such as some being exposed to oxygen while others are exposed to anaerobic conditions, and because of changes in carbon supply gradients, cellulose synthesis might be unequal. Bacterial cellulose has been in much use over plant cellulose due to it being in much greater quantity than plant cellulose. It shows much profit with the terms of cost-effective manufacturing, free from impurities, and much wider scope than plant cellulose. The structural property of bacterial cellulose aids in understanding the potential uses and drawbacks of the composition in order to configure the magnitude and way of production. Cellulose is made up of linear homopolysaccharides connected by 1,4-glycosidic connections (Figure 6) and conjugated by β -D-glucose units (Figure 6). This is due to the unique 3D structure of bacterial cellulose, which accounts for its better physical qualities as compared to vegetal cellulose. Bacterial cellulose fibrils, for example, form extensive aggregate networks with an average diameter of 1.5 nm, resulting in significantly increased surface area, flexibility, elasticity, and tensile strength.

Following the successful production of cellulose exopolysaccharides, the linear chains of cellulose are organized into 10–15 polymer chains, resulting in nanofibers that are then sequentially structured to produce microfibrils that are 100 times smaller than their vegetal counterparts. Microfibril bundles are formed by bundling the microfibrils together (Figure 6). Microfibril bundles are formed by bundling the microfibrils together. The microfibril bundles are grouped together to produce cellulose ribbons that are 3–4 nm thick and 70–80 nm broad. These ribbons then randomly intertwine to produce a thick matrix of cellulose fibers, which is formed by strong inter- and intrachemical interaction, principally hydrogen bonding, that happens between consecutive sheets of cellulose. This high amount of hydrogen bonding also permits cavities to develop inside the cellulose, which has an ionic charge that allows elements like silver ions to be implanted into the material. This characteristic of cellulose will enable manipulations such as loading the cellulose with antibacterial compounds having an ionic charge aiming at organisms causing harm. Bacterial cellulose has shown flexibility with lipophilic molecules used in ice cream production and gum as a lipid substitute, production in coconut milk fermentation, and amalgamating constancy with an increase in manufacturing.

The unique structure of nanofiber encompasses hydroxyl groups and crystalline structure with hydrogen bonds for improved hydrophilicity and possible hydrophobicity owing to its nanocrystal's matrix [41]. It is seen that these nanocrystals can interact with lipophilic molecules even without a hydrophobic group.

3.7. Bacterial Biosurfactants. These are commonly known as microbial surfactants; they are known to produce microorganisms which are said to be in dual nature towards aqueous medium being hydrophilic and hydrophobic. Some commonly known microbes are yeast, bacteria, and fungi. Bacterial biosurfactants comprises of glycolipid, lipopeptides, lipoproteins, fatty acids, polysaccharides, and phospholipids [42]. The structural composition of a biosurfactant is a polar hydrophobic tail with a polar head group linked with a carbon chain group. Agricultural production is negatively impacted by changing climatic circumstances such as increasing temperatures, unpredictable rainfall, and biotic and abiotic stress factors. Agronomists, researchers, and the scientific community are also concerned about the emergence of new pests, pathogens, or plant diseases. Indeed, for pathogen control or plant disease management, a bigger population in both industrialized and developing nations relies on chemical pesticides or agrochemicals. Yet, the prolonged and unrepresentative use of agrochemicals results in hazardous chemical residues in food, poor nutritional quality, and the rise of pesticide-resistant diseases. Agrochemical deposition also has an unfavorable impact on the texture, nutritional quality, and natural microflora of the soil, as well as causing environmental issues by damaging soil and water habitats. In the last two decades, however, microorganisms and their products have been widely used to improve agricultural productivity and crop output, as well as to reduce harmful and dangerous environmental pollutants. Microbes are also preferred in numerous industries for sustainable development and production due to their diverse nature, simple production methods, cost-effectiveness, and minimal or no hazardous influence on the surrounding environment.

Biosurfactants are one of the most recently discovered microbially generated biomolecules, and they are widely used as raw materials in the agriculture, waste management, and pharmaceutical sectors for lubrication, wetting, and

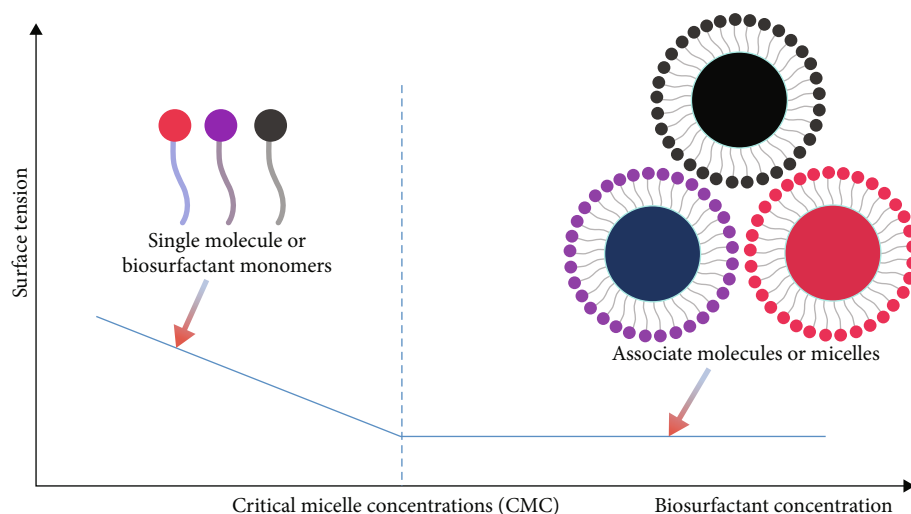


FIGURE 7: Critical micelle formation (CMC) and combination of micelles with other biosurfactant monomers. Reproduced from [43]. Copyright 2021, Antioxidants (MDPI).

other activities. We observe that when these biosurfactants aggregate, i.e., monomers (Figure 7), with each other, they form a compact associate molecules or micelles (Figure 7) at a particular temperature enough to activate and produce the desired results.

The quality and quantity of biosurfactants, on the other hand, are dependent on a number of elements, including the kind of microbe, medium additives, substrate nature, and many internal and external conditions during microbial culture development. The fundamental procedure in the synthesis of biosurfactants is the selection of microbial strains. Therefore, during the exponential or stationary phases of development, when nutritional levels are restricted, biosurfactant production occurs either intracellularly or extracellularly in the microbial strain. The composition of biosurfactants (Figure 7) is also influenced by the source and separation tactics of microorganisms; for example, a strain isolated from a polluted location is regarded a good candidate for contaminant degradation. The idea behind this is that the isolated bacterium may employ the contamination as a food source. Biosurfactants (Figure 7) also play a physiologic factor in improving the bioavailability of hydrophobic molecules involved in cellular activation and development processes, as well as facilitating the absorption of carbon sources found in the soil. Indeed, the physiological aspect of biosurfactant generation in a polluted site is unknown, although it is thought to improve nutrient absorption from hydrophobic substrates, biofilm development, and cellular motility by lowering surface tension at the phase boundary. During the study of biosurfactant molecules, quick and reliable methods for the isolation and screening of microbial strains, as well as subsequent assessment of their involvement in emulsification, lowering interfacial, or surface tension, are key aspects. Bushnell and Hass discovered biosurfactants generated by the microorganisms *Corynebacterium simplex* and *Pseudomonas aeruginosa* in early 1941. Microbial growth depends on the presence of carbon (C) and nitrogen (N) sources in the medium. In both

laboratory and large-scale industrial fermenters, the type, quantity, and ratio of carbon and nitrogen in the medium have a direct impact on microbial growth and biosurfactant synthesis. Most research employed glucose, sucrose, and glycerol as carbon and yeast extract, respectively, and NaNO_3 , urea, and soya broth as a nitrogen source in the medium. For example, for optimal biosurfactant formation, an abundance of carbon sources and nitrogen limitation are desired. For *Pseudomonas* species, for example, a C/N ratio of 20 has been determined to be the most beneficial. The most favorable use has been in the detergents, emulsifiers, wetting, and foaming agents and also to promote solubilization of hydrophobic substances [44].

3.8. Hyaluronic Acid. Hyaluronic acid (HA) (Figure 8) also known as hyaluronan is a linear, negatively charged comprising of repeated structure of β -1,4 D glucuronic acid and β -1,3-N-acetyl-D-glucosamine disaccharide units as shown in Figure 8. Hyaluronic acid has been found to be a cornerstone to beauty industry due its immense hydrophilicity trait.

The nanostructured polyelectrolyte complex was modified with polycation chitosan and then used as an enveloping agent towards menthol and eugenol to provide slow growth of microbes. There is more work to be needed in the upcoming days.

4. Biomedical Application

In the industrial arena, nanostructured polymeric materials can be used to improve a wide range of biological applications including wound healing devices, pharmacological patches, glues, and drug carriers. Application of vegetable oil-based polymeric materials can increase the biodegradation of the material. Various biomedical application essential materials range from soft to hard. In human metabolism, both endogenous compounds such as glycerol and sebacic acid in two monomers are found.

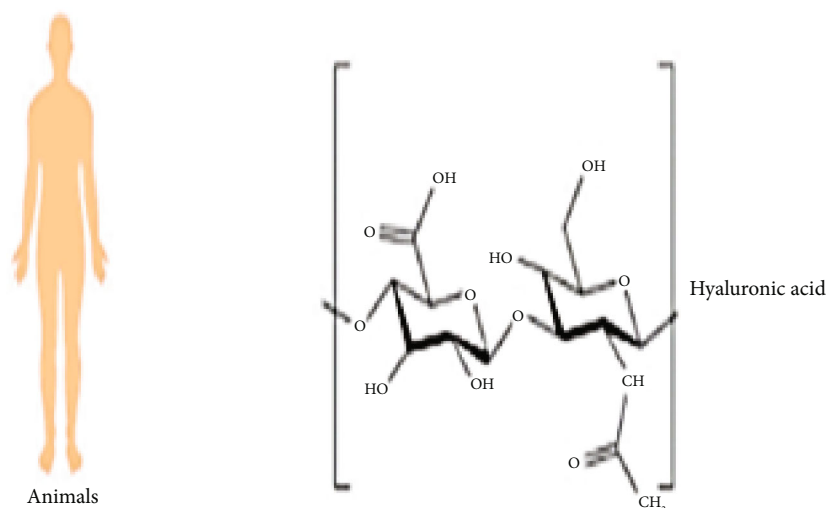


FIGURE 8: Schematic representation of chemical structure of hyaluronic acid. Reproduced from [15]. Copyright 2020, Molecules (MDPI).

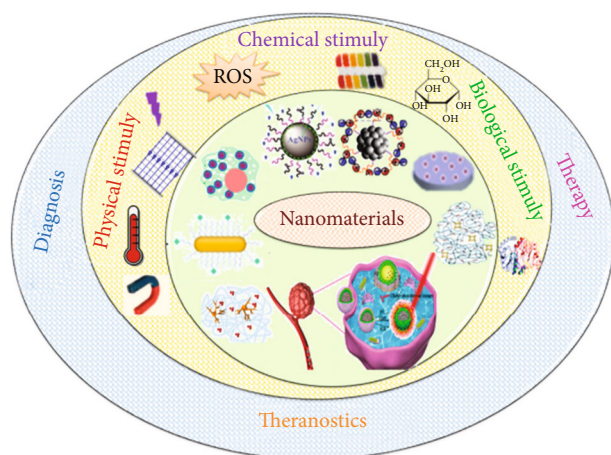


FIGURE 9: Biomedical applications of smart nanomaterials as a function of their nanostructure. Reproduced from [51]. Copyright 2021, Nanomaterials, MDPI.

Cis platinum and paclitaxel exhibit localized antitumor agent delivery [45–48]. Similarly, polymers were utilized for controlled release of peptide drugs and protein [49]. Treatment of osteomyelitis is used in the delivery of gentamicin sulphate and used in delivery of local anesthetics [50]. On the other hand, the harder materials such as polyurethane polymeric soya bean oil polystyrene membranes system are mainly based on the sunflower oils and soya bean. They were exploring for tissue engineering showing encouraging proliferation and cell adherence (Figure 9). Various examples of physioresponsive nanomaterials and their biomedical applications are reported in Table 1. Several examples of chemical-responsive nanomaterials and their biomedical applications are discussed in Table 2. Several examples of biological-responsive nanomaterials and their biomedical applications are discussed in Table 3. Various research papers such as dual and multiresponsive nanomaterials and their biomedical applications are reported in Table 4.

For monitoring the release of anticancer drugs, a drug carrier system based on the redox-responsive P[(2-((camptothecin)-oxy)ethyl) disulfanyl)ethylmethacrylate]-co-(2-(D-galactose)methylmethacrylate)] (P(MACPTS-co-MAGP)) and AgNPs has been developed. The anticancer medication camptothecin (CPT) is bound to the surface of AgNPs through a redox-sensitive disulfide bond on the side chain of P(MACPTS-coMAGP) (Figure 1). Reversible addition-fragmentation chain transfer (RAFT) polymerization of monomers of 2-(D-galactose) methylmethacrylate (MAGP) and 2-(2-((camptothecin)-oxy)ethyl)disulfanyl) ethylmethacrylate (MACPTS) coupling with CPT yielded P(MACPTS-coMAGP). MAGP units with a D-galactose structure have a high biocompatibility and are commonly employed in medicine. Disulfide bonds, a well-known redox-responsive structure, have long been used in drug delivery systems to stimulate drug release. Additionally, disulfide bonds have a strong interaction with metal nanoparticles, allowing them to easily bind to their surfaces. As a result, the distance between CPT and AgNPs is near enough to meet the requirements. The NSET effect causes CPT fluorescence to be suppressed (“off”). When a reducing agent, such as glutathione, is present (GSH), because of this, the CPT molecule is released from the hybrid nanoparticles. The disulfide link is cleaved, allowing the disulfide bond to be recovered: CPT fluorescence (“on” state). As a result, the stimulus-responsive system anticancer medicine delivery and monitoring are both possible with a complicated system. CPT is released when the fluorescence “turn-on” signal of CPT is activated (as seen in Figure 1).

5. Conclusion and Future Prospects

The promising era of science and technology has led to the fact that some trustworthy natural nanostructured polymers are in the aim of being biodegradable and sustaining in nature. Natural nanostructured derivative polymers have proven its capacity of overtaking the synthetic polymers. There has been environmentally favored unsheathing

TABLE 1: Various examples of physioresponsive nanomaterials and their biomedical applications.

Sr. no.	Nanomaterials	Application	References
1.	3D collagen hydrogel	Directed neuronal regeneration	[52]
2.	Fe ₃ O ₄ /MePEG-PLA nanocapsules	MRI	[53]
3.	Ruthenium-containing block copolymer poly-Ru nanoparticles	In vivo photodynamic therapy and photochemotherapy	[54]
4.	Poly(ethylene glycol) PEG	Switchable fluorescent probes	[55]
5.	Fe ₃ O ₄ /polyaniline Fe ₃ O ₄ /PANI	Fe ₃ O ₄ /polyaniline Fe ₃ O ₄ /PANI	[56]
6.	Polyaniline/gold nanocomposite PANI/AuNCs	Immunosensor detection of chronic kidney disease	[57]
7.	Poly(catechol)/graphene Oxide/graphene sheet suspension/AuNP/pol/gr/GCEs	DNA biosensor/electrochemical biosensors/lymphoblastic leukemia	[58]
8.	Gold nanoparticles	Drug delivery, photothermal platform, and skin wound healing	[59]
9.	Nanofibers of biodegradable poly(L-lactide) (PLLA)/poly(lactide-co-glycolide) (PLGA)	Drug delivery	[60]
10.	PMASH magnetic nanocapsules	Tumor therapy	[61]
11.	Polyaniline, poly(3,4-ethylenedioxythiophene) PANIP, and PEDOT	Neural prostheses	[62]

TABLE 2: Various examples of chemical-responsive nanomaterials and their biomedical applications.

Sr. no.	Nanomaterials	Application	References
1.	Octasulfonate-modified zinc (II) phthalocyanine (ZnPcS ₈) and layered double hydroxide (LDH)	Theranostics	[63]
2.	P(MACPTS-co-MAGP)@AgNPs nanoparticles/P(MACPTS-co-MAGP)@AgNPs	Drug release	[64]
3.	Folate redox-responsive chitosan nanoparticles FTC-NPs	Anticancer drug delivery	[65]
4.	Hyaluronic acid-functionalized nanoparticles/(HACSLA-NPs)	Breast cancer therapy	[66]
5.	PEGylated redox-responsive nanoscale COFs (denoted F68@SS-COFs)	Cancer therapy	[67]
6.	Hybrid nanotransistor	Receptor-mediated endocytosis in tumor cells	[68]
7.	Melanin-like nanoparticles	Photoacoustic imaging of tumors	[69]
8.	PEG-Ag NPs	Antibacterial, wound healing	[70]
9.	Poly(ethylene glycol)	Prodrug for breast cancer cells	[71]
10.	AgNPs hybrid nanoparticles	Drug delivery	[72]

TABLE 3: Various examples of biological-responsive nanomaterials and their biomedical applications.

Sr. no.	Nanomaterial	Application	References
1.	(CMCS-PBA-LV) NPs/liposomal nanoparticles	Oral administration of insulin	[74]
2.	ATP-ag nanoparticles/chitosan-based multifunctional nanocarriers	Participate in signal transduction and protein activity	[75]
3.	Silver nanoparticles	Therapeutic delivery	[76]
4.	Mesoporous silica nanoparticles-silver nanoparticles	Tissue growth in vivo process	[77]
5.	Hyaluronic acid- (HA-) coated calcium carbonate NP	Oral insulin delivery	[78]
6.	Chitosan/poly(gamma-glutamic acid) nanoparticles	Oral insulin delivery	[79]
7.	Boronic acid-derived polymers	Drug delivery	[80]
8.	ATP-Ag nanoparticles	Participate in signal transduction and protein activity	[81]

techniques, and emulsifying polysaccharides have proven to be cost reliable in terms of isolation of a nanopolymer matrix from biopolymers. Nanostructured natural polymers

have expressed in synthesizing different biopolymers to some useful chemical structures. Since polysaccharide are available in bulk, it is seen that there is maximum

TABLE 4: Examples of dual and multiresponsive nanomaterials and their biomedical applications.

Sr. no.	Nanomaterial	Application	References
1.	(LAE-co-PGDE-co-Lys) core-crosslinked nanocarrier	Anticancer drug delivery	[82]
2.	Nanogels based on alginate and cystamine	Anticancer drug delivery	[83]
3.	Poly(ethylene glycol) nanoparticles PLL-ICG	Photothermal and photodynamic therapy	[84]
4.	Histidine-4 polyamidoamine dendrimer Nanocarrier	Anticancer drug delivery	[85]
5.	Poly(NIPAM) nanogel @ Fe ₃ O ₄ NPs	Anticancer drug delivery	[86]
6.	Silica-coated mesoporous carbon nanocomposite (MCN@Si)	Chemophotothermal therapy of tumor	[87]
7.	Magnetic nanoparticles MFNPs	Targeting, drug delivery, and MR	[88]
8.	2-hydroxyethylmethacrylate (HEMA)/ <i>N,N'</i> -bis(acryloyl)cystamine (BACy)/poly(<i>N</i> -isopropylacrylamide) (PNIPAM)/methacrylic acid (MAA)	Drug delivery	[89]
9.	Poly(ethylene oxide, 2-(diethylamino)ethyl methacrylate	Drug release	[90]
10.	Six-arm star-shaped amphiphilic copolymer with poly(caprolactone)-bpoly(acrylic acid)-b-poly(poly(ethylene glycol) methyl ether methacrylate)	Anticancer drug delivery	[15]

productivity and chemical composition of material from it. However, the setback is all given. In conclusion, all three citrus pectin samples depicted similarity in their characterization studies, and because of the high mucoadhesive nature of pectin, we believe them to be suitable carriers for oral delivery of hydrophobic drug in controlled dosage forms. We plan to conduct a detailed drug delivery studies in the near future based on the developed and well-characterized pectin nanoparticles. The dissolving rate of lignin and also pectin has proven to be challenging. As a result, there is less nutritional content and a less agitated digestive system, which can lead to major health problems if consumed on a regular basis without medical supervision. Modified citrus pectin (MCP), a modified kind of pectin, on the other hand, has properties that make it digestible. Pectin might be useful in cancer therapy. MCP seemed to slow prostate cancer development. Pectin needs advancement in terms of biodegradability in order to sustain the biological environment. Before any judgments concerning MCP's potential as an anticancer drug can be reached, larger, better-designed research are required. In environmental remediation, starch-based materials offer a more cost-effective and environmentally benign alternative to petroleum-based polymers. Though starch is an organic nanomaterial with several features such as renewability, biodegradability, abundance, eco-friendliness, cheap cost, nontoxic, weak barrier, and mechanical qualities, raw starch has poor processability, high brittleness, and high hydrophilicity. As a result, physical and/or chemical processes such as gelatinization, etherification, esterification, crosslinking, grafting, oxidation, and enzymatic hydrolysis are used to modify starch, while the physical qualities of gum Arabic are affected by tree age and processing circumstances. Moisture, total ash, volatile matter, and other quality characteristics have been developed internal power. Because Arabic gum contains a variety of amino acids, it boosts antioxidant capability. Arabic gum is employed as a medication carrier in the pharmaceutical sector since it is nontoxic. It is thought to be a biologically

innocuous chemical. Starch-based materials contain a wide range of functions and/or unique characteristics, which are mostly linked to synergetic effects and have been documented in environmental remediation applications. Various natural starch sources, green nanomaterial production, recyclability, and the toxicity effect of nanowaste should all be explored in future studies. For commercial use, ongoing research of biodegradable starch-based hybrids and nanomaterials emphasizing on new functional materials, processing technology, and cost reduction is required. Bacterial cellulose has been recognized as a highly adaptable material for producing medically relevant materials such as wound dressings, composites, dental grafts, and gels, all of which have unique properties that are well matched to their functions. Furthermore, bacterial cellulose biomaterials have been studied for use in a variety of biomedical applications, including the production of wound dressings for mild to severe wounds. These investigations are ongoing. Bacterial biosurfactants have a long history of helpful compatibility in terms of physical, chemical, and biological applications, making them an excellent choice for multifunctional nanopolymer composites. Bacteria are global; thus, studying these nanocomposites is easier. Biosurfactant chemicals require extensive investigation in order to develop new antibacterial, antioxidant, and antiproliferative agents. This is not only economical, but it also protects the body from the substance's hazardous effects. Biosurfactant-based cancer therapy and drug delivery, on the other hand, require further investigation for the treatment of chronic disorders. Despite advancements in technology and raw materials, biosurfactants' high manufacturing costs and low yield continue to be a challenge to overcome. Furthermore, none of these alternatives has yet to adequately address all of the issues that have arisen. The maximum propagation of natural nanostructured biopolymers with the new rising technology is still not being able to quantify its amount with the rapid on-going demands which is also challenging. When looking at the quality of the nanostructured biopolymer, the quantity

trait becomes underestimated which is also proven to be one of the major setbacks. There is still research and still opportunities of more research to be conducted. The future of nanomaterials is very bright, and it beckons all the areas of modern science.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgments

We express our sincere gratitude to the Head and Dean, Department of Chemistry, Central University of Allahabad, Prayagraj, for providing laboratory facility. The authors are very thankful to the Under Grant Commission, New Delhi, for the economic support in the form of CRET Fellowship.

References

- [1] A. Gandini and T. M. Lacerda, "From monomers to polymers from renewable resources: recent advances," *Progress in Polymer Science*, vol. 48, pp. 1–39, 2015.
- [2] F. Luzi, D. Puglia, and L. Torre, "Natural fiber biodegradable composites and nanocomposites: a biomedical application," in *Biomass, Biopolymer-Based Materials, and Bioenergy*, pp. 179–201, Woodhead Publishing, 2019.
- [3] F. J. Martin-Martinez, K. Jin, D. López Barreiro, and M. J. Buehler, "The rise of hierarchical nanostructured materials from renewable sources: learning from nature," *ACS Nano*, vol. 12, no. 8, pp. 7425–7433, 2018.
- [4] M. Wysokowski, I. Petrenko, A. Stelling, D. Stawski, T. Jesionowski, and H. Ehrlich, "Poriferan chitin as a versatile template for extreme biomimetics," *Polymers*, vol. 7, no. 2, pp. 235–265, 2015.
- [5] N. Corrigan, J. Yeow, P. Judzewitsch, J. Xu, and C. Boyer, "Seeing the light: advancing materials chemistry through photopolymerization," *Angewandte Chemie*, vol. 131, no. 16, pp. 5224–5243, 2019.
- [6] U. A. Banin, N. Waiskopf, L. Hammarström et al., "Nanotechnology for catalysis and solar energy conversion," *Nanotechnology*, vol. 32, no. 4, article 042003, 2020.
- [7] Y. Wang, A. Vogel, M. Sachs et al., "Current understanding and challenges of solar-driven hydrogen generation using polymeric photocatalysts," *Nature Energy*, vol. 4, no. 9, pp. 746–760, 2019.
- [8] P. A. DeSario, J. J. Pietron, T. H. Brintlinger et al., "Oxidation-stable plasmonic copper nanoparticles in photocatalytic TiO₂ nanoarchitectures," *Nanoscale*, vol. 9, no. 32, pp. 11720–11729, 2017.
- [9] T. Naseem and T. Durrani, "The role of some important metal oxide nanoparticles for wastewater and antibacterial applications: a review," *Environmental Chemistry and Ecotoxicology*, vol. 3, pp. 59–75, 2021.
- [10] S. Wu, T. Wang, and X. Hangxun, "Regulating heterogeneous catalysis of gold nanoparticles with polymer mechanochemistry," *ACS Macro Letters*, vol. 9, no. 9, pp. 1192–1197, 2020.
- [11] S. Navalón, A. Dhakshinamoorthy, M. Álvaro, and H. García, "Diamond nanoparticles in heterogeneous catalysis," *Chemistry of Materials*, vol. 32, no. 10, pp. 4116–4143, 2020.
- [12] J. Prakash, J. C. Pivin, and H. C. Swart, "Noble metal nanoparticles embedding into polymeric materials: from fundamentals to applications," *Advances in Colloid and Interface Science*, vol. 226, no. Part B, pp. 187–202, 2015.
- [13] D. Roper, K. R. Berry, J. R. Dunklin et al., "Effects of geometry and composition of soft polymer films embedded with nanoparticles on rates for optothermal heat dissipation," *Nanoscale*, vol. 10, no. 24, pp. 11531–11543, 2018.
- [14] S. Goyal, N. B. Hernández, and E. W. Cochran, "An update on the future prospects of glycerol polymers," *Polymer International*, vol. 70, no. 7, pp. 911–917, 2021.
- [15] A. Massironi, A. Morelli, D. Puppi, and F. Chiellini, "Renewable polysaccharides micro/nanostructures for food and cosmetic applications," *Molecules*, vol. 25, no. 21, p. 4886, 2020.
- [16] T. A. Debele, S. L. Mekuria, and H.-C. Tsai, "Polysaccharide based nanogels in the drug delivery system: application as the carrier of pharmaceutical agents," *Materials Science and Engineering*, vol. 68, pp. 964–981, 2016.
- [17] F. J. Heiligtag and M. Niederberger, "The fascinating world of nanoparticle research," *Materials Today*, vol. 16, no. 7–8, pp. 262–271, 2013.
- [18] D. A. Scott, "A review of ancient Egyptian pigments and cosmetics," *Studies in Conservation*, vol. 61, no. 4, pp. 185–202, 2016.
- [19] S. Bayda, M. Adeel, T. Tuccinardi, M. Cordani, and F. Rizzolio, "The history of nanoscience and nanotechnology: from chemical–physical applications to nanomedicine," *Molecules*, vol. 25, no. 1, p. 112, 2020.
- [20] P. Sciau, L. Noé, and P. Colomban, "Metal nanoparticles in contemporary potters' master pieces: Lustre and red "Pigeon blood" potteries as models to understand the ancient pottery," *Ceramics International*, vol. 42, no. 14, pp. 15349–15357, 2016.
- [21] J. Jeevanandam, A. Barhoum, Y. S. Chan, A. Dufresne, and M. K. Danquah, "Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations," *Beilstein Journal of Nanotechnology*, vol. 9, no. 1, pp. 1050–1074, 2018.
- [22] D. Schaming and H. Remita, "Nanotechnology: from the ancient time to nowadays," *Foundations of Chemistry*, vol. 17, no. 3, pp. 187–205, 2015.
- [23] A. Ravindran, P. Chandran, and S. Sudheer Khan, "Biofunctionalized silver nanoparticles: advances and prospects," *Colloids and Surfaces B: Biointerfaces*, vol. 105, pp. 342–352, 2013.
- [24] J. Mathew, J. Joy, and S. C. George, "Potential applications of nanotechnology in transportation: a review," *Journal of King Saud University-Science*, vol. 31, no. 4, pp. 586–594, 2019.
- [25] R. Vittal and K.-C. Ho, "Zinc oxide based dye-sensitized solar cells: a review," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 920–935, 2017.
- [26] S. De, A. M. Balu, J. C. van der Waal, and R. Luque, "Biomass-derived porous carbon materials: synthesis and catalytic applications," *ChemCatChem*, vol. 7, no. 11, pp. 1608–1629, 2015.
- [27] R. Wu, K. Liu, J. Ren et al., "Cellulose nanocrystals extracted from grape pomace with deep eutectic solvents and application for self-healing nanocomposite hydrogels," *Macromolecular Materials and Engineering*, vol. 305, no. 3, article 1900673, 2020.

- [28] C. Hervé, A. Rogowski, A. W. Blake, S. E. Marcus, H. J. Gilbert, and J. P. Knox, "Carbohydrate-binding modules promote the enzymatic deconstruction of intact plant cell walls by targeting and proximity effects," *Proceedings of the National Academy of Sciences*, vol. 107, no. 34, pp. 15293–15298, 2010.
- [29] S. A. A. Mohamed, M. El-Sakhawy, and M. A.-M. El-Sakhawy, "Polysaccharides, Protein and Lipid -Based Natural Edible Films in Food Packaging: A Review," *Carbohydrate Polymers*, vol. 238, article 116178, 2020.
- [30] H. C. Arca, L. I. Mosquera-Giraldo, V. Bi, D. Xu, L. S. Taylor, and K. J. Edgar, "Pharmaceutical applications of cellulose ethers and cellulose ether esters," *Biomacromolecules*, vol. 19, no. 7, pp. 2351–2376, 2018.
- [31] N. K. Mandlekar, *Integration of wood waste to develop multi-functional fully biobased textile structure*, Soochow University, China, 2019.
- [32] S. Beisl, A. Miltner, and A. Friedl, "Lignin from micro- to nanosize: production methods," *International Journal of Molecular Sciences*, vol. 18, no. 6, p. 1244, 2017.
- [33] F. R. Wurm and C. K. Weiss, "Nanoparticles from renewable polymers," *Frontiers in Chemistry*, vol. 2, p. 49, 2014.
- [34] F. Rol, M. N. Belgacem, A. Gandini, and J. Bras, "Recent advances in surface-modified cellulose nanofibrils," *Progress in Polymer Science*, vol. 88, pp. 241–264, 2019.
- [35] D. O. Bokov, R. I. Sharipova, O. G. Potanina et al., "Polysaccharides of crude herbal drugs as a group of biologically active compounds in the field of modern pharmacognosy: physico-chemical properties, classification, pharmacopoeial analysis," *Proteins*, vol. 2, pp. 4–6, 2020.
- [36] S. Zhang, G. I. N. Waterhouse, F. Xu et al., "Recent advances in utilization of pectins in biomedical applications: a review focusing on molecular structure-directing health-promoting properties," *Critical Reviews in Food Science and Nutrition*, vol. 61, pp. 1–34, 2021.
- [37] S. M. Avramescu, C. Butean, C. V. Popa, A. Ortan, I. Moraru, and G. Temocico, "Edible and functionalized films/coatings—Performances and perspectives," *Coatings*, vol. 10, no. 7, p. 687, 2020.
- [38] L. Han, B. Hu, R. Ma et al., "Effect of arabinogalactan protein complex content on emulsification performance of gum arabic," *Carbohydrate Polymers*, vol. 224, p. 115170, 2019.
- [39] S. Ahmad, M. Ahmad, K. Manzoor, R. Purwar, and S. Ikram, "A review on latest innovations in natural gums based hydrogels: preparations & applications," *International Journal of Biological Macromolecules*, vol. 136, pp. 870–890, 2019.
- [40] F. Fahma, Sugiarto, T. C. Sunarti, S. M. Indriyani, and N. Lidayana, "Thermoplastic cassava starch-PVA composite films with cellulose nanofibers from oil palm empty fruit bunches as reinforcement agent," *International Journal of Polymer Science*, vol. 2017, 5 pages, 2017.
- [41] H. Kargarzadeh, M. Mariano, D. Gopakumar et al., "Advances in cellulose nanomaterials," *Cellulose*, vol. 25, no. 4, pp. 2151–2189, 2018.
- [42] J. D. Desai and I. M. Banat, "Microbial production of surfactants and their commercial potential," *Microbiology and Molecular Biology Reviews*, vol. 61, no. 1, pp. 47–64, 1997.
- [43] A. Kumar, S. K. Singh, C. Kant et al., "Microbial biosurfactant: a new frontier for sustainable agriculture and pharmaceutical industries," *Antioxidants*, vol. 10, no. 9, p. 1472, 2021.
- [44] K. G. O. Bezerra, R. D. Rufino, J. M. Luna, and L. A. Sarubbo, "Saponins and microbial biosurfactants: potential raw materials for the formulation of cosmetics," *Biotechnology Progress*, vol. 34, no. 6, pp. 1482–1493, 2018.
- [45] S. Doppalapudi, A. Jain, A. J. Domb, and W. Khan, "Biodegradable polymers for targeted delivery of anti-cancer drugs," *Expert Opinion on Drug Delivery*, vol. 13, no. 6, pp. 891–909, 2016.
- [46] M. A. Farooq, M. Aquib, A. Farooq et al., "Recent progress in nanotechnology-based novel drug delivery systems in designing of cisplatin for cancer therapy: an overview," *Artificial cells, nanomedicine, and biotechnology*, vol. 47, no. 1, pp. 1674–1692, 2019.
- [47] W. Zhang, C. Li, C. Shen et al., "Prodrug-based nano-drug delivery system for co-encapsulate paclitaxel and carboplatin for lung cancer treatment," *Drug Delivery*, vol. 23, no. 7, pp. 2575–2580, 2016.
- [48] Z. Zhang, M. Lin, and S.-S. Feng, "Paclitaxel drug delivery systems," *Expert Opinion on Drug Delivery*, vol. 10, no. 3, pp. 325–340, 2013.
- [49] Q. Cheng and Y. Liu, "Multifunctional platinum-based nanoparticles for biomedical applications," *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, vol. 9, no. 2, article e1410, 2017.
- [50] M. Lucke, B. Wildemann, S. Sadoni et al., "Systemic versus local application of gentamicin in prophylaxis of implant-related osteomyelitis in a rat model," *Bone*, vol. 36, no. 5, pp. 770–778, 2005.
- [51] M. Aflori, "Smart nanomaterials for biomedical applications—a review," *Nanomaterials*, vol. 11, no. 2, p. 396, 2021.
- [52] M. Antman-Passig and O. Shefi, "Remote magnetic orientation of 3D collagen hydrogels for directed neuronal regeneration," *Nano Letters*, vol. 16, no. 4, pp. 2567–2573, 2016.
- [53] B. Xu, H. Dou, K. Tao et al., "Two-in-one" fabrication of Fe₃O₄/MePEG-PLA composite nanocapsules as a potential ultrasonic/MRI dual contrast agent," *Langmuir*, vol. 27, no. 19, pp. 12134–12142, 2011.
- [54] W. Sun, S. Li, B. Häupler et al., "An amphiphilic ruthenium polymetallo-drug for combined photodynamic therapy and photochemotherapy in vivo," *Advanced Materials*, vol. 29, no. 6, article 1603702, 2017.
- [55] R. Klajn, "Spiropyran-based dynamic materials," *Chemical Society Reviews*, vol. 43, no. 1, pp. 148–184, 2014.
- [56] M. K. Hossain, H. Minami, S. M. Hoque et al., "Mesoporous electromagnetic composite particles: electric current responsive release of biologically active molecules and antibacterial properties," *Colloids and Surfaces B: Biointerfaces*, vol. 181, pp. 85–93, 2019.
- [57] M. O. Shaikh, B. Srikanth, P.-Y. Zhu, and C.-H. Chuang, "Impedimetric immunosensor utilizing polyaniline/gold nanocomposite-modified screen-printed electrodes for early detection of chronic kidney disease," *Sensors*, vol. 19, no. 18, p. 3990, 2019.
- [58] M. Mazloum-Ardakani, B. Barazesh, A. Khoshroo, M. Moshtaghiun, and M. H. Sheikhha, "A new composite consisting of electrosynthesized conducting polymers, graphene sheets and biosynthesized gold nanoparticles for biosensing acute lymphoblastic leukemia," *Bioelectrochemistry*, vol. 121, pp. 38–45, 2018.
- [59] M. G. Arafa, R. F. El-Kased, and M. M. Elmazar, "Thermoresponsive gels containing gold nanoparticles as smart antibacterial and wound healing agents," *Scientific Reports*, vol. 8, no. 1, article 13674, 2018.

- [60] M. R. Abidian, D.-H. Kim, and D. C. Martin, "Conducting-polymer nanotubes for controlled drug release," *Advanced Materials*, vol. 18, no. 4, pp. 405–409, 2006.
- [61] C.-S. Chiang, Y.-S. Shen, J.-J. Liu, W.-C. Shyu, and S.-Y. Chen, "Synergistic combination of multistage magnetic guidance and optimized ligand density in targeting a nanoplatform for enhanced cancer therapy," *Advanced Healthcare Materials*, vol. 5, no. 16, pp. 2131–2141, 2016.
- [62] J. Liu, Y. S. Kim, C. E. Richardson et al., "Genetically targeted chemical assembly of functional materials in living cells, tissues, and animals," *Science*, vol. 367, no. 6484, pp. 1372–1376, 2020.
- [63] X. Li, B.-Y. Zheng, M.-R. Ke, Y. Zhang, J.-D. Huang, and J. Yoon, "A tumor-pH-responsive supramolecular photosensitizer for activatable photodynamic therapy with MinimalIn VivoSkin phototoxicity," *Theranostics*, vol. 7, no. 10, pp. 2746–2756, 2017.
- [64] R. Singh et al., "Synthesis of three-dimensional reduced-graphene oxide from graphene oxide," *Journal of Nanomaterials*, Article ID 8731429, pp. 1–8, 2022.
- [65] E. Mazzotta, S. de Benedittis, A. Qualtieri, and R. Muzzalupo, "Actively targeted and redox responsive delivery of anticancer drug by chitosan nanoparticles," *Pharmaceutics*, vol. 12, no. 1, p. 26, 2020.
- [66] S. Rezaei, S. Kashanian, Y. Bahrami, L. J. Cruz, and M. Motiei, "Redox-sensitive and hyaluronic acid-functionalized nanoparticles for improving breast cancer treatment by cytoplasmic 17α -methyltestosterone delivery," *Molecules*, vol. 25, no. 5, p. 1181, 2020.
- [67] S. Liu, J. Yang, R. Guo, L. Deng, A. Dong, and J. Zhang, "Facile fabrication of redox-responsive covalent organic framework nanocarriers for efficiently loading and delivering doxorubicin," *Macromolecular Rapid Communications*, vol. 41, no. 4, article 1900570, 2020.
- [68] Y. Wang, C. Wang, Y. Li et al., "Digitization of endocytic pH by hybrid ultra-pH-sensitive nanoprobe at single-organelle resolution," *Advanced Materials*, vol. 29, no. 1, article 1603794, 2017.
- [69] U. Sivasankaran and K. G. Kumar, "A cost effective strategy for dual channel optical sensing of adrenaline based on 'in situ' formation of copper nanoparticles," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 223, article 117292, 2019.
- [70] K.-Y. Ju, J. Kang, J. Pyo, J. Lim, J. H. Chang, and J.-K. Lee, "pH-induced aggregated melanin nanoparticles for photoacoustic signal amplification," *Nanoscale*, vol. 8, no. 30, pp. 14448–14456, 2016.
- [71] X. Xie, T. C. Sun, J. Xue et al., "Ag nanoparticles cluster with pH-triggered reassembly in targeting antimicrobial applications," *Advanced Functional Materials*, vol. 30, no. 17, article 2000511, 2020.
- [72] N. B. Mutlu-Agardan, C. Sarisozen, and V. P. Torchilin, "Cytotoxicity of novel redox sensitive PEG2000-S-S-PTX micelles against drug-resistant ovarian and breast cancer cells," *Pharmaceutical Research*, vol. 37, no. 3, pp. 1–8, 2020.
- [73] L. Qiu, L. Zhao, C. Xing, and Y. Zhan, "Redox-responsive polymer prodrug/AgNPs hybrid nanoparticles for drug delivery," *Chinese Chemical Letters*, vol. 29, no. 2, pp. 301–304, 2018.
- [74] S. Mollazadeh, M. Mackiewicz, and M. Yazdimamaghani, "Recent advances in the redox-responsive drug delivery nano-platforms: a chemical structure and physical property perspective," *Materials Science and Engineering: C*, vol. 118, article 111536, 2021.
- [75] L. Li, G. Jiang, W. Yu et al., "Preparation of chitosan-based multifunctional nanocarriers overcoming multiple barriers for oral delivery of insulin," *Materials Science and Engineering: C*, vol. 70, Part 1, pp. 278–286, 2017.
- [76] L. P. Datta, A. Chatterjee, K. Acharya, P. de, and M. Das, "Enzyme responsive nucleotide functionalized silver nanoparticles with effective antimicrobial and anticancer activity," *New Journal of Chemistry*, vol. 41, no. 4, pp. 1538–1548, 2017.
- [77] S. T. Gunawan, K. Kempe, T. Bonnard et al., "Multifunctional thrombin-activatable polymer capsules for specific targeting to activated platelets," *Advanced Materials*, vol. 27, no. 35, pp. 5153–5157, 2015.
- [78] D. Liu, G. Jiang, W. Yu et al., "Oral delivery of insulin using CaCO_3 -based composite nanocarriers with hyaluronic acid coatings," *Materials Letters*, vol. 188, pp. 263–266, 2017.
- [79] K. Sonaje, Y.-J. Chen, H.-L. Chen et al., "Enteric-coated capsules filled with freeze-dried chitosan/poly(γ -glutamic acid) nanoparticles for oral insulin delivery," *Biomaterials*, vol. 31, no. 12, pp. 3384–3394, 2010.
- [80] W. Tang and C. Cheng, "Hydrogel-based colloidal photonic crystal devices for glucose sensing," *Polymers*, vol. 12, no. 3, p. 625, 2020.
- [81] R. Biba, P. P. Štefanić, P. Cvjetko, M. Tkalec, and B. Balen, "Silver nanoparticles phytotoxicity mechanisms," in *Silver Nanomaterials for Agri-Food Applications*, pp. 317–356, Elsevier, 2021.
- [82] Q. Hu, Y. Wang, L. Xu, D. Chen, and L. Cheng, "Transferrin conjugated pH- and redox-responsive Poly(Amidoamine) dendrimer conjugate as an efficient drug delivery carrier for cancer Therapy," *International journal of nanomedicine*, vol. 15, pp. 2751–2764, 2020.
- [83] X. Xu, X. Wang, W. Luo et al., "Triple cell-responsive nanogels for delivery of drug into cancer cells," *Colloids and Surfaces B: Biointerfaces*, vol. 163, pp. 362–368, 2018.
- [84] P. Zhang, Z. Gao, J. Cui, and J. Hao, "Dual-stimuli-responsive polypeptide nanoparticles for photothermal and photodynamic therapy," *ACS Applied Bio Materials*, vol. 3, no. 1, pp. 561–569, 2020.
- [85] Y. Shi, S. Shan, C. Li et al., "Application of the tumor site recognizable and dual-responsive nanoparticles for combinational treatment of the drug-resistant colorectal cancer," *Pharmaceutical Research*, vol. 37, no. 4, pp. 1–14, 2020.
- [86] Y. Huang, Z. Tang, S. Peng et al., "pH/redox/UV irradiation multi-stimuli responsive nanogels from star copolymer micelles and Fe^{3+} complexation for "on-demand" anticancer drug delivery," *Reactive and Functional Polymers*, vol. 149, article 104532, 2020.
- [87] H. Lu, Q. Zhao, X. Wang et al., "Multi-stimuli responsive mesoporous silica-coated carbon nanoparticles for chemophotothermal therapy of tumor," *Colloids and Surfaces B: Biointerfaces*, vol. 190, article 110941, 2020.
- [88] D. Bhattacharya, B. Behera, S. K. Sahu, R. Ananthkrishnan, T. K. Maiti, and P. Pramanik, "Design of dual stimuli responsive polymer modified magnetic nanoparticles for targeted anti-cancer drug delivery and enhanced MR imaging," *New Journal of Chemistry*, vol. 40, no. 1, pp. 545–557, 2016.

- [89] B. Yu, N. Song, H. Hu, G. Chen, Y. Shen, and H. Cong, "A degradable triple temperature-, pH-, and redox-responsive drug system for cancer chemotherapy," *Journal of Biomedical Materials Research Part A*, vol. 106, no. 12, pp. 3203–3210, 2018.
- [90] W. Chen and D. Jianzhong, "Ultrasound and pH dually responsive polymer vesicles for anticancer drug delivery," *Scientific Reports*, vol. 3, no. 1, pp. 1–9, 2013.