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Applications of Cellulose-Based Nanomaterials for Sustainability and Therapeutics: A Review

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Abstract

Cellulose is a natural fibrous carbohydrate, is the main structural element of plant cell walls, and is the most abundant natural polymer found in the biosphere. Due to its abundance and chemical stability, it has been used as a raw material in various industries for thousands of years. Due to developments in nanotechnology, materials that are used in macroscale abundantly are also utilized for nanomaterial design, and cellulose-based nanomaterials have gained more interest in recent years. The unique properties of cellulose-based nanomaterials including their chemical stability, high degree of crystallinity, biocompatibility, biodegradability, and tunability of their chemical (e.g., surface modification) and physical (e.g., shape) properties make them good candidates for functional nanomaterial design. This review brings advances in cellulose-based nanomaterials for application in two major fields, sustainability and therapeutics.

Keywords: Cellulose, Drug delivery, Nanomaterial, Tissue engineering, Wastewater treatment

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1 Introduction

Improvements in the life standards of human beings result in an increased need for textile products, which results in increased textile waste. In the textile and clothing industry, the most utilized material is cotton, and approximately 88–96 % of this natural fiber contains cellulose [1–3]. In recent years, there has been an increased interest in the production of greener materials by using cellulose isolated from cotton waste, which may be further utilized for the development of environmentally friendly technologies.

Cellulose is a natural polysaccharide polymer that is the essential element of plant cell walls, and it is the most abundant biomaterial found in the biosphere [4]. Cellulose has a water-insoluble and fibrous nature, which is crucial to maintaining the structure of plant cell walls [4]. In 1838, the molecular formula of cellulose was reported as $C_6H_{10}O_5$ by Anselme Payen [4]. In the structural view, cellulose contains linear chains of glucose monomers, which are linked by β-1,4-glycosidic bonds [5]. The cellulose microfibril (CM) structure occurs with aggregation of glucan chains with both hydrogen bonds and van der Waals interactions, forming a long thread-like crystalline structure [5].

Further investigations on cellulose revealed that different types of cellulose exist, which are categorized concerning the physical and chemical properties of the protein structure, and these polymorphs are named cellulose I, II, III, and IV [5, 6]. Cellulose I is the native and the most common cellulose that exists as parallel sheets without inter-sheet hydrogen bonding and can be converted into cellulose II and III. On the other hand, cellulose II is the most stable structure which is formed via immersion of native cellulose in an alkaline solution and exists as antiparallel strands connected by inter-sheet hydrogen bonding. With liquid ammonia treatments, cellulose I and II can be converted to cellulose III, while further treatment of cellulose III at high temperatures with glycerol results in the formation of cellulose IV [5, 6].

Cellulose is marketed in different forms such as microcrystalline cellulose (MCC), microfibrillated cellulose (MFC), CMs, cellulose nanocrystals (CNCs), nanofibrillated cellulose, and bacterial cellulose (BC) [7]. MCCs are microlevel cellulose particles with both length and width >1 µm. MFCs are individual fibers with a length >10 µm and a width in the range of 2–20 µm, and they can be produced from wood via either chemical or mechanical treatment [7]. CNCs are produced from cellulose-based raw materials via acid hydrolysis, and they have a length in the range of 50–500 nm and a width in the range of 2–20 nm [8].

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Production of nanosized cellulose materials can solve problems associated with hierarchical structure defects, which can be seen in microsized cellulose materials and can bring additional superiorities such as larger surface area [7]. Cellulose nanomaterials are described as the nanosized products or extracts of native cellulose [8, 9], which have diverse forms including rod, needle, spherical, or ribbonlike and have lengths in the range of 50–1000 nm and diameter in the range of 3–50 nm [10, 11]. The nanocellulose surface can be further modified chemically via covalent bond formation with the functional groups [12], and the high charge of cellulose colloids provides high stability and prevents aggregation of nanoparticles [13].

Utilization of cellulose-based nanomaterials has many properties like renewability, biocompatibility, biodegradability, chemical stability, high specific surface, no/low toxicity, high degree of crystallinity, and tunability of their chemical (e.g., surface modification) and physical (e.g., shape) properties [4, 14]. In this manner, the usage of cellulose nanomaterials can be opportunistic, especially in biomedical applications (such as drug delivery, tissue regeneration and repair, biosensing, and substitute implants) [14]. By the way, numerous studies were generated in the name of cellulose nanomaterials, and many novel nanocellulose types were designed.

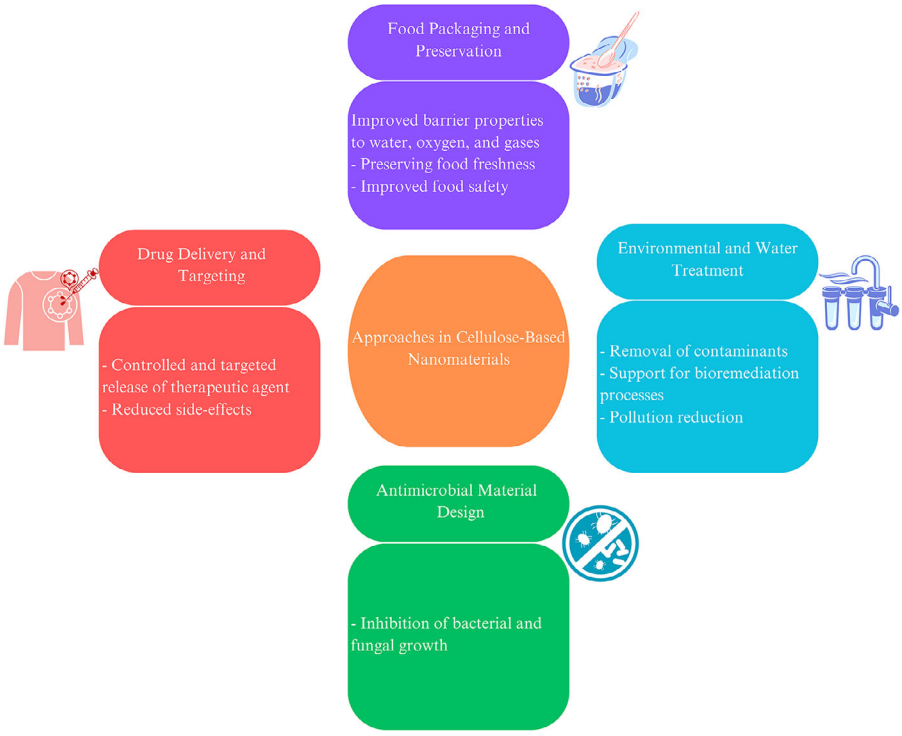

Figure 1. Graphical representation of different approaches in the use of cellulose-based nanomaterials for sustainability and therapeutics including environmental and water treatment, antimicrobial material design, food packaging/preservation, and drug delivery/targeting.

Cellulose-based nanomaterials are categorized into three main classes, which are CNCs, cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC). The first class is CNCs, also named nanocrystalline cellulose, which are needlelike or rigid rodlike nanowhiskers with 5–70 nm width and 200–500 nm length [14]. The second class is CNFs, also named nano-/microfibrillated cellulose, which has a nanoscale diameter (<100 nm) and length of several micrometers [14, 15]. The last class is BNC, in which cellulose is produced via bacteria, and the nanomaterial is produced as pure and ribbon-shaped nanofibers with 20–100 nm diameter and length of several micrometers [4, 14]. These three classes of cellulose-based nanomaterials can be utilized in many eras under different names such as nanowires, nanorods, nanoballs, nanowhiskers, nanotubes, nanodiamonds, and nanocoils [14].

Cellulose-based nanomaterials have many well-known advantageous features such as biodegradability, biocompatibility, and hydrophilicity, and beyond these features, many recent advances may provide the development of superior materials. In recent years, there has been an increased interest in the development of novel biohybrid materials by integrating specific microorganisms with electrospun cellulose-based nanofibrous materials. Although, in general, electrospun nanofibrous cellulosic materials have much bigger sizes (>100 nm diameter) compared with classical CNFs, applications of these materials for pollutant removal purposes are also included in this review because their size is still at the nanoscale, and very promising results have been reported for applications of these materials as a potential carrier system for integrating with bioremediative microorganisms. This review highlights the recent breakthroughs in the application of cellulose-based nanomaterials across two major fields, sustainability and therapeutics, which involve wastewater treatment, food packaging, development of antimicrobial materials for potential therapeutic use, and drug delivery specifically. Fig. 1 summarizes these different applications of cellulose-based nanomaterials schematically.

2 Applications of Cellulose-Based Nanomaterials for Sustainability

2.1 Cellulose-Based Nanomaterials for Wastewater Treatment

There are many opinions in the scientific community that access to clean drinking water will be one of the most important problems of the world in the not-too-distant future [16]. Access to safe, clean, and drinkable water is a standard requirement for every human being, as water is the basic substance for the

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survival of every living organism. However, the point where the industry has come and the treatment methods have difficulty in meeting the demand for clean water for the increasing human population has revealed the need for the development of new and more effective treatment methods. As a result of nanotechnological developments, new and more effective strategies for wastewater treatment have been proposed, and promising results have been obtained for removing pollutants in water, preventing or reducing toxicity caused by these pollutants, and ultimately achieving clean and drinkable water [16–18].

For a long time, wastes or by-products from agriculture have been used as potential adsorbent materials for water-cleaning purposes. Cellulose here is the major component of all agricultural wastes and by-products. However, this practice is not always flawless, and some problems may occur when using agricultural wastes or by-products as adsorbents, which may include inadequate performance for adsorption when using these materials in their raw form and potential color leaching problems. These problems have been reported to be overcome by chemical or physical modification of these materials [19] which may include milling or nanomilling for gaining new characteristics.

When compared with synthetic polymer-based adsorbents, cellulose-based nanomaterials are natural, abundant, nontoxic, biodegradable, and very efficient adsorbents. In addition, the surface chemistry of cellulose-based nanomaterials can be further modified to develop more effective adsorbents, making them ideal bio-adsorbents for use in wastewater treatment [7, 20]. Therefore, these low-cost, eco-friendly, and nontoxic materials have been extensively studied to develop bio-adsorbents for the remediation of heavy metals in water systems [17, 18, 21, 22].

The adsorbent nature of cellulose-based nanomaterials comes from their carboxylic functional groups, which provide adsorption of cations (e.g., cationic metal ions) due to the electrostatic force between the negatively charged carboxylate groups and the metallic cations found in the water [4]. In addition, chemical modification of the hydroxyl group on the anhydroglucose unit (e.g., replacing it with amine orthiol) has been found to improve the heavy metal adsorption capacity of cellulose-based nanomaterials [4]. Cellulose-based nanomaterials have been reported to be potentially effective adsorbents for the remediation of some heavy metal cations including Cr (VI), Cu (II), Co (II), Cd (II), Ni (II), Pb (II), and Hg (II) [4, 23–25]. In a recent study, it has been shown that cellulose-based nanomaterials can also adsorb gold from a chloride solution with high efficiency (98 %) [26].

In addition to heavy metal cations, the removal of various other water pollutants can also be accomplished via the utilization of cellulose-based nanomaterials including organic dyes, oils, pharmaceuticals, etc. [27]. Due to the presence of varying functional groups (e.g., hydroxyl and carboxyl), nanocellulose-based materials have a high potential for the removal of various organic pollutants as well, specifically pesticides (e.g., atrazine, simazine, cyprazine, and ametryn) [28], petroleum-based products (e.g., ethylene gas and toluene) [29, 30], organic dyes (e.g., methylene blue, rhodamine B, and methyl orange) [31, 32], and pharmaceutics (e.g., potassium diclofenac and tylosin antibiotic) [33, 34], in which removal performances of cellulose-based nanomaterials are assumed to be provided by differential interactions (e.g. electrostatic interactions, hydrogen bonding, $\pi-\pi$ interactions, and van der Waals forces) that occur between pollutants and these nanomaterials [27].

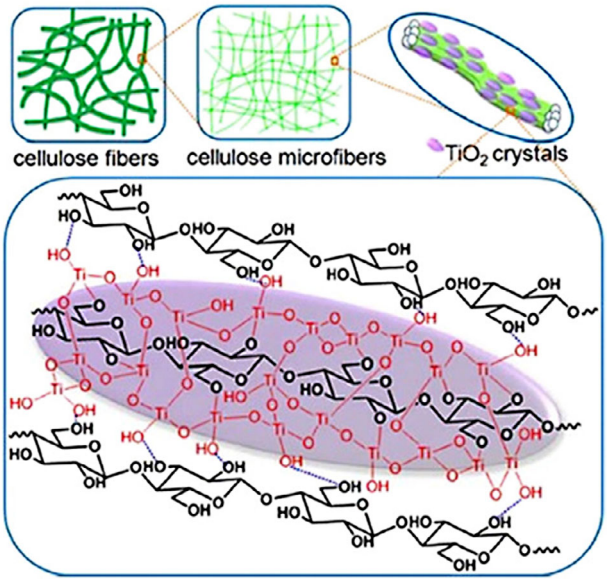

Figure 2. Schematic representation for chemical modification of cellulose with TiO_2. Reproduced from [23] with permission from Elsevier.

The adsorption capacity of cellulose-based nanomaterials can be further improved by modification of their chemical architecture, such that, in a recent study, Karimi et al. (2016) reported a very high Cu(II) adsorption capacity for cellulose-based nanomembranes developed via 2,2,6,6-teramethylpiperidinyloxy (TEMPO) oxidation (374 mg g^{-1}), more than three times higher than other bio-adsorbents (in general <100 mg g^{-1}) [35], which was assumed to be because of the large active surface area along with the higher numbers of carboxylate groups [4]. In another study, the formation of titanium dioxide (TiO_2) nanocrystals on cellulose fibers (CFs) via facile hydrolysis of $TiOSO_4$ has been reported, and the newly developed TiO_2/CF composite has shown high adsorption capability with superior regenerability and selectivity for Pb(II) remediation (Fig. 2) [23].

Up to this part, the wastewater treatment studies mentioned above were based on adsorption without the involvement of biological entities, and they cannot be classified under biotechnological applications. Nevertheless, cellulose-based nanomaterials can also be utilized as a potential carrier material for bioremediative microorganisms, which enables the development of novel biohybrid materials with bioremediation capability due to the existence of integrated microorganisms. Although dead bio-adsorptive microorganisms or their specific enzymes could be utilized for this purpose, live microorganisms may also be integrated with such cellulose-based nanomaterials. Cellulose-based nanofibrous materials produced via the electrospinning method have been offered as potential carrier systems in recent years, and they have been utilized for the integration of specific microorganisms for the remediation of water pollutants.

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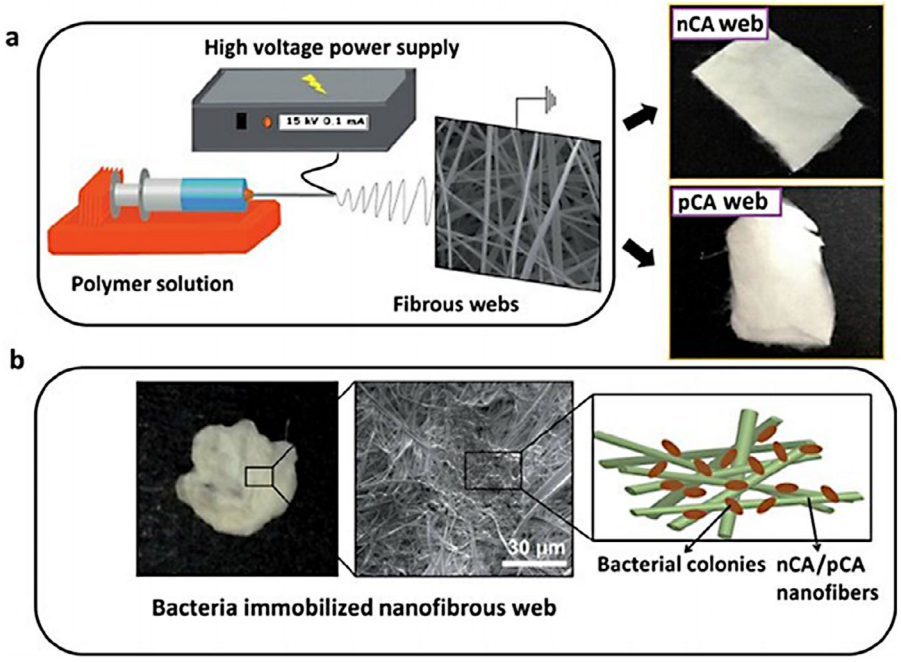

Figure 3. (a) Graphical representation of the electrospinning procedure for the production of nCA and pCA nanofibrous webs along with their photographic images, (b) sequential images of bacteria-immobilized nanofibrous webs including a photographic image, an SEM micrograph, and schematic illustration of bacterial cells on nanofibrous surfaces. Reproduced from [37] with permission from the Royal Society of Chemistry.

In terms of developing bio-integrated cellulose-based nanomaterials for potential wastewater treatment applications, Prof. Uyar's research group has reported several promising studies in recent years [36–38]. In one of their studies, they developed ammonium remediating biohybrid system by immobilizing a previously isolated ammonia-oxidizing bacterial strain, *Acinetobacter calcoaceticus* STB1, on electrospun porous cellulose acetate (CA) nanofibrous webs by natural adhesion of bacterial cells onto nanofibrous surfaces during 35 days of incubation in bacterial growth medium [36]. Samples of CA nanofibrous webs were collected after the end of the incubation period and checked via scanning electron microscope (SEM) imaging for the attachment of bacterial cells. After being sure that the bacterial attachment was sufficient for further experiments, samples of bacteria-immobilized CA web samples were utilized in ammonium removal experiments. Pristine CA webs and free *Acinetobacter calcoaceticus* STB1 cells were also included as control samples in these experiments, where the samples were incubated in a basal growth medium containing different concentrations of ammonium (50 mg L^{-1} as low, 100 mg L^{-1} as medium, and 200 mg L^{-1} as high) at 140 rpm and 30 °C for 48 h. The results indicated that bacteria-immobilized CA webs could successfully remediate ammonium at each concentration, and their removal performance was very similar to free bacteria, while pristine CA webs remediated only a negligible amount of ammonium, suggesting that the ammonium removal capability of biohybrids mainly came from the metabolic activities of the immobilized bacteria. In addition, results indicated that the remediation performances of bacteria-immobilized webs were negatively correlated with the initial ammonium concentrations of samples, such that complete removal was achieved for 50 mg L^{-1} of initial ammonium concentration, while the percentile removal was 98.5 % for 100 mg L^{-1} and 72 % for 200 mg L^{-1} initial concentration of ammonium. Bacteria-immobilized CA webs were also tested for potential reusability of ammonium removal, and the results indicated that they could be utilized at least several times without a significant loss in their ammonium removal capability [36].

In another study, Prof. Uyar's research group developed a novel biohybrid material for remediation of a known dye pollutant, methylene blue, in water systems by immobilizing three different bacterial species, *Pseudomonas aeruginosa*, *Clavibacter michiganensis*, and *Aeromonas eucrenophila*, on electrospun CA nanofibrous webs by natural adhesion of bacterial cells onto nanofibrous surfaces during 7 days of incubation in bacterial growth medium [38]. Samples of CA nanofibrous webs were collected after 7 days of incubation and checked via SEM imaging for attachment of bacterial cells. After observing strong biofilm structures on the surfaces of CA nanofibrous webs, bacteria-immobilized CA webs were incubated in media containing 20, 100, 250, and 500 mg mL^{-1} of initial methylene blue dye concentrations. While nearly complete dye removal (at least 95 % for each) was observed at 20 mg L^{-1} of initial methylene blue dye concentration for three different types of bacteria-immobilized CA web samples, much lower dye decolorization performances were observed at higher initial concentrations (100, 250, and 500 mg L^{-1}), suggesting that the decolorization capabilities of bacteria-immobilized webs were negatively correlated with the initial dye concentrations. The reusability of these three different bacteria-immobilized CA web samples was also checked in reusability experiments, and the results indicated that they could preserve their dye removal capabilities even after several times of reuse [38].

Prof. Uyar's research group also evaluated if differences in CA webs' fiber morphology were influential on the bacterial immobilization and thereby remediation performances of the newly developed biohybrids in a separate study [37]. For this study, novel electrospun biohybrid materials have been developed by natural adhesion of previously isolated surfactant degrading bacterial strains *Serratia proteamaculans* STB3 and *Achromobacter xylosoxidans* STB4 on either electrospun porous CA (pCA) or non-porous CA (nCA) nanofibrous webs (Fig. 3). It was found that at initial stages, bacterial attachment on pCA webs

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was lower than on nCA webs, implying that porous surfaces might have been difficult to settle at earlier stages, yet after 21 days of incubation, similar amounts of bacterial attachment could be achieved for both nCA and pCA web samples. Sodium dodecyl sulfate (SDS) was utilized as the model surfactant in bioremediation experiments, and the results indicated that bacteria-immobilized pCA nanofibrous webs could remediate SDS with higher efficiency, which was assumed to be mainly based on the differences in available surface area for those two different nanofibrous webs for the attached bacteria, causing differences in their SDS remediation performances eventually. The reusability of both bacteria-immobilized nCA and pCA webs was evaluated as well, and they were found to be potentially reusable for use in SDS bioremediation [37].

2.2 Cellulose-Based Nanomaterials for Food Packaging

Food is one of the fundamental requirements in human life, and preserving food freshness and safety is the main purpose of food industries. Food waste is reaching millions of tons each year, and many foods are wasted due to spoilage issues. With proper packaging techniques, this waste can be eliminated to a significant extent [39, 40]. Food packaging should provide physical protection as barriers to water and gases and should be developed as eco-friendly. Besides ensuring physical protection, maintaining food quality and safety during transportation and storage is also a crucial concern [41].

There are divergent food packaging materials that aim to protect food from the external environment in a cost-effective manner. Requirements in food packaging differ according to the intrinsic properties of food (e.g., oxidation potential), extrinsic factors (e.g., temperature), and the required shelf-life. Concerning the properties of the food, packaging material can be determined like metalized biofilms used for low-moisture foods (e.g., nuts), glass and polyethylene terephthalate (PET) mostly used for high-moisture foods (e.g., milk), and mostly derivatives of polyethylene used for fresh foods (e.g., meat/dairy products). Unfortunately, most of these materials are synthetic and non-degradable, causing environmental concerns [42].

Utilization of nanotechnological developments provides many opportunities. Specifically, natural polymers have a great potential to reduce food spoilage and environmental pollution; also, they have biodegradable, nontoxic, sustainable, reprocessable, and recyclable characteristics. Owing to the fibrous and water-insoluble characteristics of cellulose, nanomaterial types produced by this natural polymer could significantly fulfill these expectations [41, 43]. There are divergent examples in food packaging with cellulose-based nanomaterials, which include CNCs, CNFs, and BNC, to generate improved barrier properties to water and gases [41].

CNCs can be synthesized by undergoing chemical or enzymatic hydrolysis, and most of the time, the highly concentrated acid hydrolysis method is preferred since acids have lower costs and shorter reaction times than enzymes. However, the usage of highly concentrated acid is an energy-consuming and environmentally hazardous method, while enzymatic acid usage is much more beneficial since it is environmentally friendly and has a much higher yield and selectivity [44–46]. The synthesized CNCs have features like high crystallinity, high surface-to-volume ratio, and high flexibility and provide a better barrier to gas molecules [41, 44, 46]. Regarding this, de Oliveira et al. (2019) reported that CNCs obtained from agro-industrial residues can be utilized to produce water-absorbing aerogels to be used in food packaging. In the production of CNCs, they utilized the enzyme hydrolysis method, which makes it a biodegradable and environmentally friendly food packaging method [46].

CNFs are cellulose-based nanomaterials that can be effectively utilized in food packaging. Recently, they have gained considerable attention as a bio-friendly and sustainable option for packaging and gas barrier applications. This attention is related to the properties of CNFs like their abundant natural availability, renewability, and biodegradability [47]. In a structural context, the main feature that distinguishes CNFs from CNCs is the aspect ratio of CNFs which is comparatively large. This size difference is mainly due to the fabrication process of CNF including only mechanical treatment that breaks fibrils into small units [39]. Recent studies on CNFs have presented novel methods; one example is the usage of edible food packaging (EFP) films. This innovative approach offers numerous beneficial features, including varying thickness levels, optical characteristics, water resistance, reduced water sensitivity, improved mechanical properties, antioxidant capabilities, and antimicrobial properties [48].

In EFP, the source of cellulose can be agricultural residue, bacterial species (e.g., BNC), algal source, or marine animal. Plant-sourced cellulose is majorly called lignocellulosic biomass, which includes cellulose, hemicellulose, and lignin [49]. For cellulose extraction from these sources, different physical, chemical, or enzymatic treatments such as high-pressure homogenization, alkali hydrolysis, acid hydrolysis, or enzymatic hydrolysis can be applied [49–53]. Eventually, the pretreated cellulose is found in the form of BNC, CNC, or cellulose nanofibrils (CNFs).

In order to improve gas and water vapor barrier, multiple coating layers are commonly utilized, especially in the combination of metalized biofilms and synthetic polymers such as polyethylene [42, 54]. However, these materials hardly dissolve in nature; therefore, the usage of natural polymers such as cellulose-based nanomaterials for packaging can be much more beneficial. Cellulose nanomaterials such as CNFs are water sensitive, and in high humidity, oxygen barrier levels may be diminished. Utilization of multiple coating layers can improve its barriers against this handicap and make it proper for food packaging applications. For instance, CNF can be combined with an extruded polylactic acid (PLA) layer to reduce moisture levels [54]. Also, a multilayer with CNF and CNC combination can be generated to use with their gas barrier characteristic for dry food; however, CNC is also water sensitive, so humidity may be still a problem in that combination, and to improve water sensitivity, the packaging material can be supported with biobased polyethylene [54, 55].

For multiple coating layer systems in food packaging methods, multilayers of natural polymers can also be used. BNC is an exopolysaccharide nanocellulose substrate that is produced extracellularly by several nonpathogenic bacteria, for

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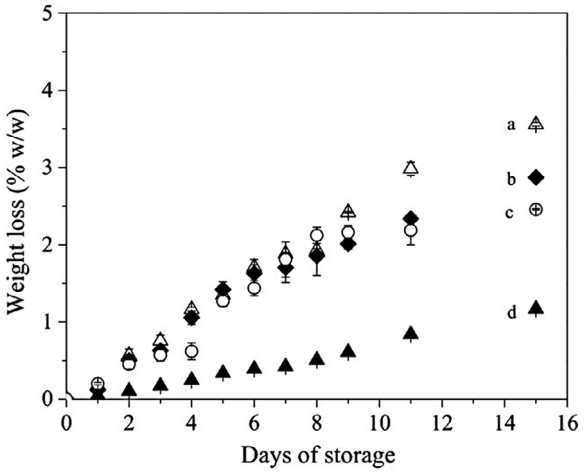

Figure 4. Loss of weight for strawberries in terms of % w/w which were sealed with either PVC-based (▲), SFMPI-based (Δ), SFMPI-NCC-based (◊), and SFMPI-BNC-based (○) biofilms (stored isothermally for ~15 days at 10 °C). Different letters (a–d) show statistically significant differences ($p < 0.05$). Reproduced from [58] with permission from Springer Nature Group.

instance, *Komagataeibacter xylinus* [56, 57]. Biodegradability and renewability characteristics are common in nanocellulose materials; beyond that, BNCs also have some divergent features like superior mechanical strength, high crystallinity, high thermal stability, and high purity [58]. Efthymiou et al. (2022) reported a useful example for food packaging with BNCs [58]. In that research, BNC was combined with sunflower meal protein isolate (SFMPI) and generated SFMPI–BNC-based biofilms on the packaging of fresh strawberries (Fig. 4). The biofilm was observed with effective preservation at 10 °C according to microbial growth and physicochemical profile such as weight loss, chemical composition, color, firmness, and respiration activity [59].

Another example of natural polymer combinations is a food packaging method with multilayers of chitosan and carboxymethyl nanocellulose. Shi et al. successfully produced a food packaging paper with high antibacterial and strong barrier characteristics by generating multilayers of chitosan and carboxymethyl nanocellulose on paper. They generated mechanically strengthened paper with improved barrier characteristics against grease, oil, vapor, and water [60, 61]. Owing to its biocompatible, nontoxic, antibacterial, and fungicidal properties, chitosan membrane is a commonly used material in especially EFP era [62].

Cellulose-based nanomaterials can also be combined with sustainable polymers such as PLA [63]. PLA is known for its biodegradable, processable, renewable, and biocompatible characteristics, and owing to its mechanical and thermal properties, PLA-based composites are often utilized in packaging and medical industries [63–65]. The main supplement of PLA is lactic acid, which can be produced through the fermentation of agricultural waste [64, 65]. Andrade et al. indicated that the utilization of CNCs improves packaging properties such as hydrophobic characteristics, thermal stability, and mechanical strength when compared to plastic-based films [65].

Beyond classical packaging methods, some designs provide intelligent packaging. Moradi et al. designed a pH-sensing indicator by using BNC and black carrot anthocyanins to observe the spoilage and freshness of fish. The indicator was observed with various color changes from red to gray according to the changing pH ranging between 2 and 11 (Fig. 5) [61, 66].

There are various application models of cellulose-based nanomaterials in the food packaging era owing to their environmentally friendly characteristics. The available food packaging methods mostly utilize non-biodegradable substances that increase environmental pollution due to plastic waste. Therefore, replacing non-biodegradable materials with biodegradable ones would help to reduce pollution and help for efficient and more environmentally friendly packaging methods (Fig. 6) [67] (Fig. 7).

Some of the selected key studies for applications of cellulose-based nanomaterials in the sustainability area are listed in Tab. 1, highlighting the design of these nanomaterials and their application purposes in each subcategory: wastewater treatment and food packaging.

3 Applications of Cellulose-Based Nanomaterials for Therapeutics

3.1 Cellulose-Based Nanomaterials for Antimicrobial Material Design

The main aim of antimicrobial design is to generate materials and products with antimicrobial properties, which majorly aims to slow down or stop microbial growth [68]. Antimicrobials started to be used in 1929 with the discovery of penicillin, and until today, many other derivatives have been discovered for the treatment of infectious diseases [69]. However, extensive usage of these antibiotics causes an increase in antimicrobial resistance, which further treats human health [68, 70]. Within the developments in the nanotechnology era, there are also beneficial methods to generate antimicrobial designs without causing antimicrobial resistance [67].

Regarding the physical properties, special surface chemistry, and ideal biological properties, cellulose-based nanomaterials have a significant interest in antimicrobial applications. In the production of these nanomaterials, all three types of nanocellulose, which are CNCs, CNFs, and BNC, can be utilized. Antimicrobial designs for nanocellulose can be generated via divergent preparation methods such as surface modifications, the addition of antibiotics, combinations with metallic nanomaterials, enzymes, or composition with polymers [67].

Nanocellulose is composed of β-1,4-glucose with three active hydroxyl groups, in which surface modification can be easily formed via oxidation, esterification, or etherification, to generate new functional groups, and the functional groups that include aldehyde group and quaternary ammonium show antimicrobial characteristics. Aldehyde nanocellulose is majorly formed via oxidation by oxidants such as periodate sodium and TEMPO [69, 71]. Oxidation via periodate sodium is majorly

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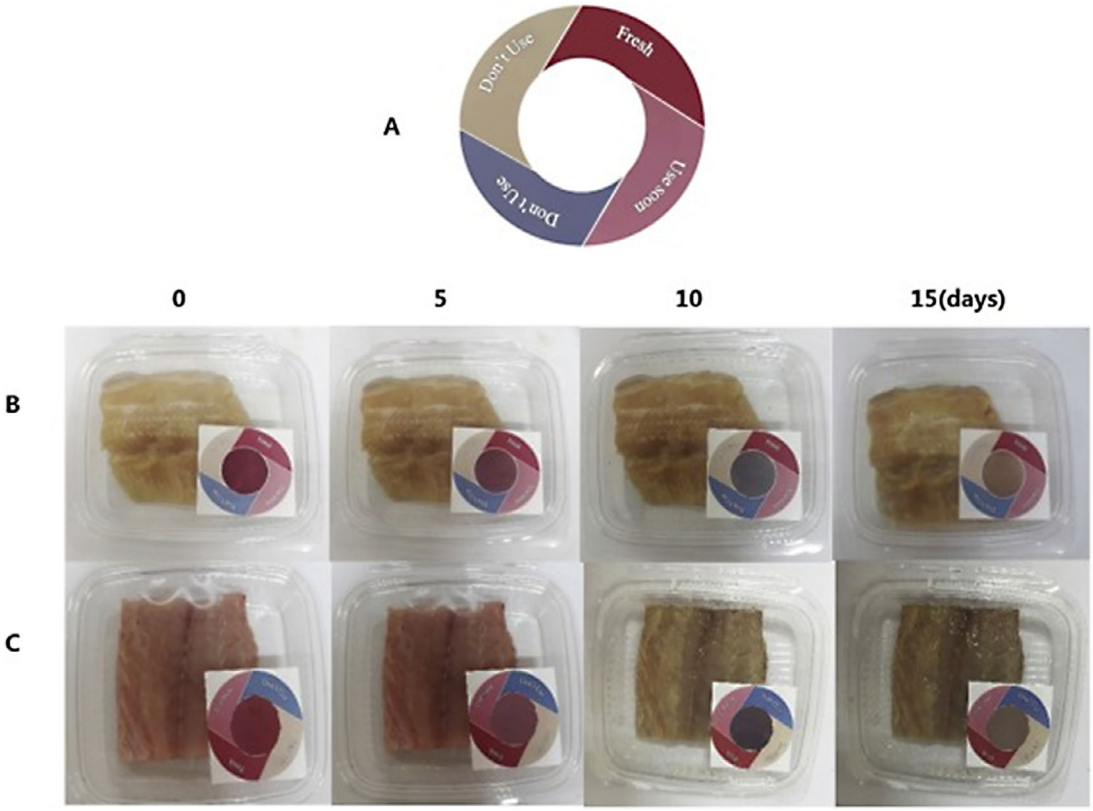

Figure 5. Graphical representation of the color label design (A) and color changes seen on the labels attached to the packages of rainbow trout (B) and common carp (C) fillets (both of them stored at 4 °C). Reproduced from [66] with permission from Elsevier.

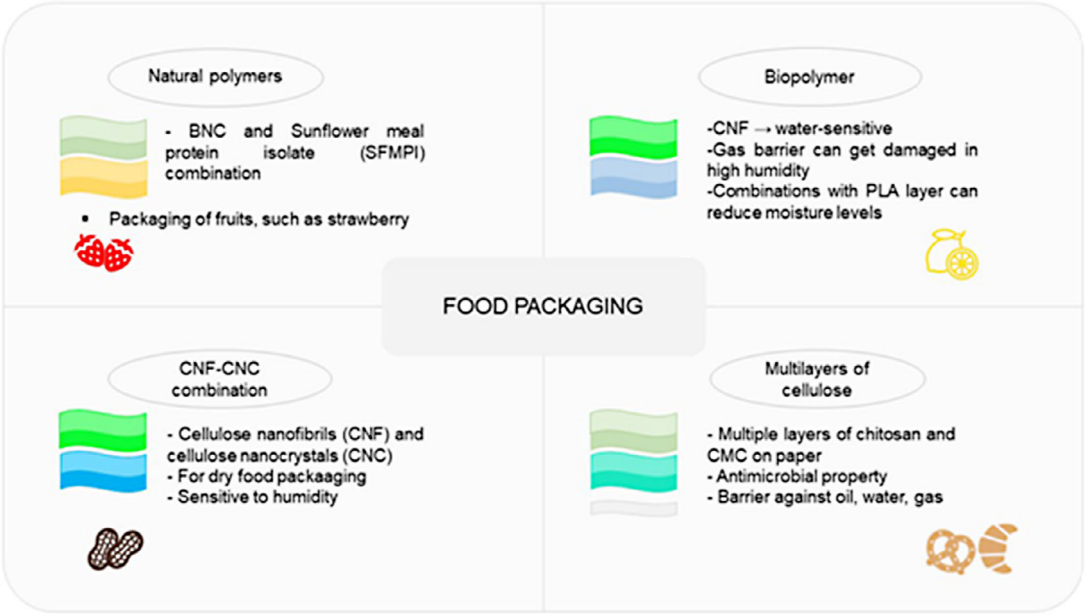

Figure 6. The application of cellulose-based nanomaterials in food packaging varies concerning the combined materials and combination method. These materials may include either natural (e.g., chitosan) or synthetic (e.g., PLA) biodegradable polymers and might be coated with multilayers of those for improved properties.

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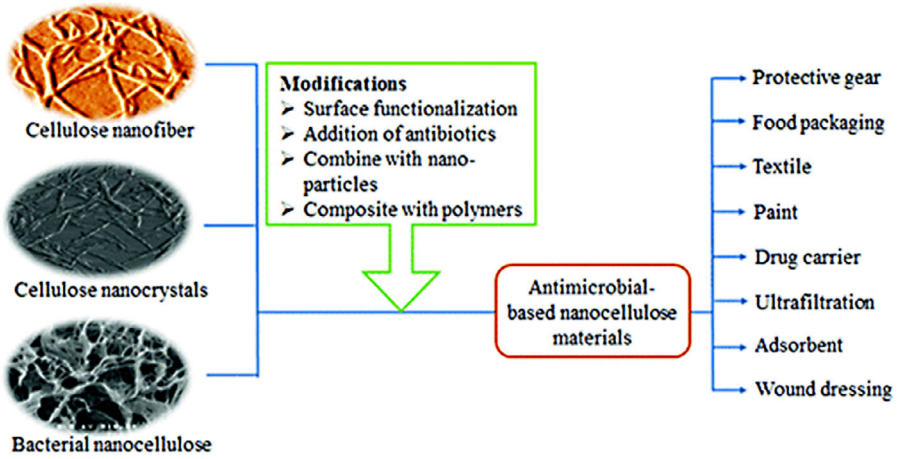

Figure 7. Different sources of nanocellulose and application of those as nanocellulose-based antimicrobial materials. Reproduced from [67] with permission from the Royal Society of Chemistry.

made in aqueous conditions, and exposure to periodate in higher concentrations with longer time helps to achieve higher aldehyde contents [69]. With the oxidation of CNFs with periodate sodium, 2,3-dialdehyde CNF is formed, which can be utilized in wound healing [67, 69]. On the other hand, TEMPO is another oxidant that can bind the surface of nanocellulose under aqueous conditions, and this newly generated aldehyde-nanocellulose form has the potential to be used in several antibacterial applications [67].

The other surface modification to design antimicrobial nanocellulose can be generated by grafting quaternary ammonium salts (e.g., dodecyl-trimethylammonium bromide) or some phosphonium salts (e.g., dodecyl-triphenyl phosphonium bromide (DDTPPBr)) [69, 71]. Nemec et al. (2022) reported that the utilization of cellulose substances in combination with an ammonium salt, tetradecyl-trimethylammonium bromide, was observed with 100 % inhibition of *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*. The positively charged ammonium groups interact with the negatively charged cytoplasmic membrane of the bacteria, and polymers are absorbed into the bacterial membrane. Further, this interaction results in the disruption of bacterial membranes [71, 72]. In addition, the combination of cellulose and a phosphonium salt, DDTPPBr, was observed with a significant bactericidal effect on the same bacteria species [72].

Also, chemicals such as pyridinium, imidazolium, and 4-vinylpyridine are commonly preferred owing to their antibacterial and antiviral characteristics, and these substances are known as environmentally friendly and low toxic [67, 70]. Produced nanocellulose-based antibacterial materials by these chemicals are majorly utilized for packaging and biochemical application purposes [67].

Antibiotic resistance continues to be a global health concern [73]. Multidrug-resistant bacteria kinds are increasing and spreading around the whole world due to overuse, misuse, or widespread use of antibiotics, and novel treatment strategies are required for treatments [74]. A combination of these antibiotics and nanocellulose mats/hydrogels is observed with a reduction of the consumption of antibiotics by bacteria and reduced antibiotic resistance risk [67]. For instance, Kaplan et al. (2014) developed cellulose hydrogels from BC by using ampicillin and gentamycin and successfully inhibited the growth of *E. coli*, *E. faecalis*, *S. aureus*, and *P. aeruginosa*, and these hydrogels can be utilized for treatments of skin wounds [75].

Silver, gold, copper, and zinc particles have strong antimicrobial activity, and a combination of these inorganic materials and nanocellulose is also used in the production of antimicrobial material design (in which these particles have properties like low toxicity, photothermal effects, and large surface area) [69, 76, 77]. The metallic nanoparticles can show their antimicrobial activity in divergent ways such as absorption of nanoparticles

Table 1. A selection of recent studies mentions applications of CBN for sustainability in different application areas, wastewater treatment, and food packaging.

Application area for CBN	Design of nanomaterials	Applications	References
Wastewater treatment	– Bacterial immobilization on electrospun CA nanofibers	– Bioremoval of ammonium – Bioremoval of methylene blue dye – Bioremediation of SDS	[36–38]
Food packaging	– Combination with natural/synthetic polymers – Combination with metalized biofilms	– Sunflower meal protein isolate (SFMPI)–bacterial-based biofilms (BNC) on the packaging of fresh strawberries – Edible food packaging via cellulose nanofibrils – Coating with multiple layers (e.g., addition of polylactic acid layer) to improve barrier properties against humidity – Combination of cellulose nanofibril and cellulose nanocrystal to achieve improved gas barrier	[42, 48, 54, 59]

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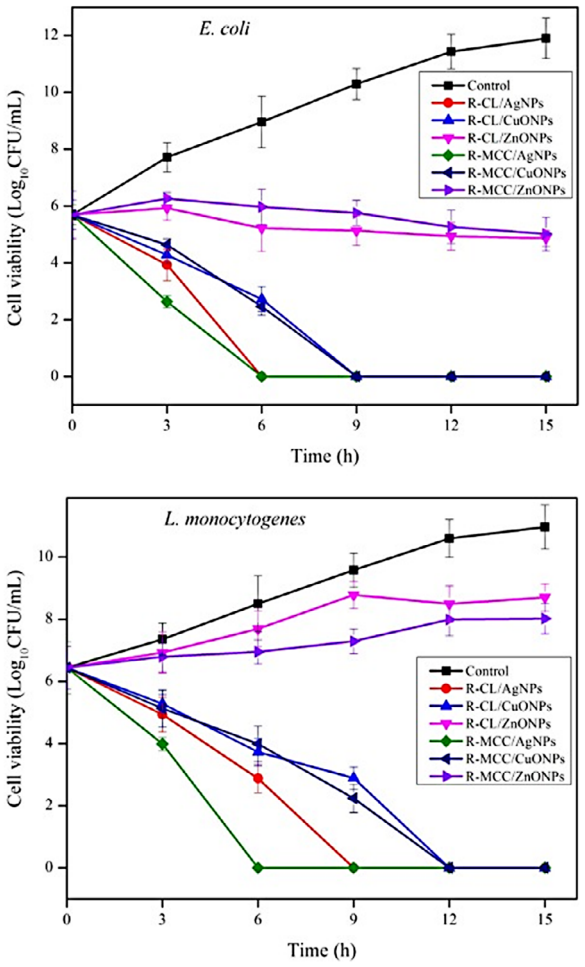

Figure 8. Antibacterial activity of different R-cellulose and metallic nanoparticle composites (CL, cotton linter; MCC, microcrystalline cellulose). Reproduced from [77] with permission from Elsevier.

on the cell wall of microbes, release of reactive oxygen species, cell membrane disruption by free radicals, the interaction of metals with respiratory enzymes, and interaction of nanoparticles with DNA and protein through sulfur and phosphorus, and their antimicrobial activity may show a difference concerning the size, shape, and synthesis method of nanoparticles [77]. After all, these antimicrobial hybrid nanomaterials can be utilized in biomedical applications such as wound healing (Fig. 8) [77].

Another antimicrobial design in cellulose-based nanomaterials is a combination of nanocellulose and antibacterial polymers: natural polymers (e.g., chitosan) and synthetic (e.g., polyhexamethylene biguanide (PHMB)) polymers [69]. A combination of chitosan, which is a natural polymer produced from chitin, and cellulose-based nanomaterials can be prepared in either physical, chemical, or biological ways. The chitosan-nanocellulose hybrid form shows antibacterial characteristics against *E. coli* and *S. aureus* when it is used as wound dressing material [78]. As a synthetic polymer, PHMB and cellulose nanomaterial combination can be generated for antimicrobial material design [79, 80]. PHMB shows an efficient antimicrobial activity, and even a low concentration of PHMB is enough for the destruction of both gram-positive and gram-negative bacteria [80]. Eventually, the produced biofilm from the nanocellulose-PHMD hybrid can be utilized in wound dressing [69].

The development of antimicrobial materials by the use of nanocellulose can also be provided by integrating with specific enzymes. In this context, Califano et al. (2021) reported on an experimental design that uses H_2O_2-producing enzymes [70]. H_2O_2 triggers an oxidative cascade reaction which may result in DNA damage, defects in protein synthesis, and disruption in the integrity of the phospholipid membrane and, therefore, can inhibit the growth of the bacteria [70, 81]. On the other hand, low concentrations of H_2O_2 may act on redox-sensitive cell signaling that supports wound healing [70].

The development of graphene oxide–cellulose nanocomposites has also been reported as a promising strategy for use in skin wound healing applications [82]. Both *in vitro* (i.e., on a human endothelial cell model) and *in vivo* (i.e., on rats) studies have been performed to evaluate the potential of this system, and the results demonstrated that graphene oxide–cellulose nanocomposites have a positive impact on skin wound healing process.

3.2 Cellulose-Based Nanomaterials for Drug Delivery

Cellulose-based nanomaterials have been reported as potential drug carrier systems, release modulators, or co-stabilizers in different forms such as cellulose nanoparticles, cellulose micelles, or cellulosic films/sheets [83]. Both hydrophobic and hydrophilic drugs have been reported to be utilized in cellulose-based drug delivery systems with the availability to administer in different routes including oral, topical, and transdermal [83]. In the following paragraphs, several recently selected studies regarding the use of cellulose-based nanomaterials for drug delivery purposes are mentioned.

Actually, in the pharmaceutical and food industry, the use of cellulose-based excipients has a very long history. On the other hand, the development of cellulose-based nanocarrier systems for drug delivery is a relatively new concept. Jackson et al. reported that pure CNC can bind with several different hydrophilic antibiotics (doxorubicin and tetracycline), and after surface modification of CNC through the use of cetyl trimethylammonium bromide (CTAB), CTAB-bound cationic CNC can bind with several nonionizing hydrophobic anticancer drugs (i.e., docetaxel, etoposide, and paclitaxel) [84]. While hydrophobic drugs have shown rapid release in the first drug delivery system, controlled drug release was observed for the hydrophobic drugs in the second drug delivery system. In another study, researchers developed a novel pH-sensitive controlled release system based on the integration of CNC and sodium alginate microspheres, and superior properties including high encapsulation efficiency, uniform swelling patterns, and sustained drug release profiles were observed for this system [85].

Valo et al. developed a novel drug delivery system by using a genetically engineered hydrophobin fusion protein having cellulose-binding domains, which is coated with itraconazole

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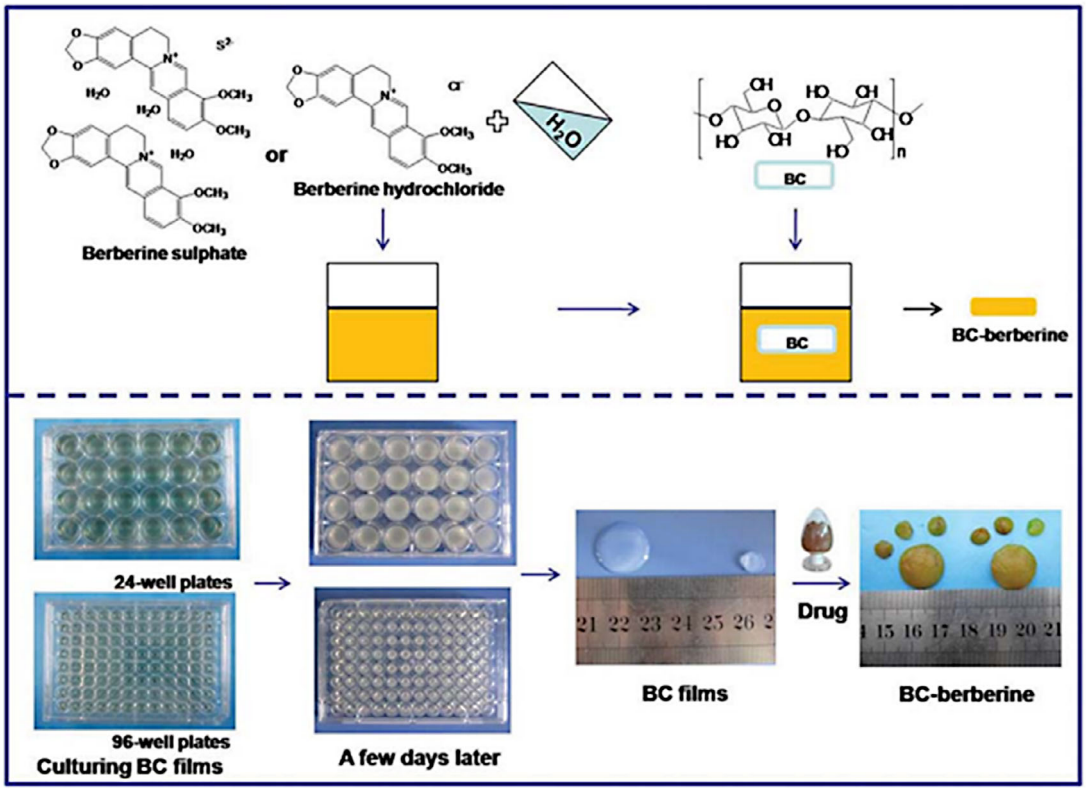

Figure 9. The representative image summarizes the experimental procedure; the chemical structures of berberine sulfate, berberine hydrochloride, and bacterial cellulose (BC); and the embedment of berberine molecules within BC. Reproduced from [87] with permission from the Royal Society of Chemistry.

drug nanoparticles and bound to CNF. It was shown that CNF in this system provided protection for drug nanoparticles and improved formulation storage stability, such that drug nanoparticles could be stored for almost a year in a carrier solution containing hydrophobin-coated CNF [86]. Huang et al. compared the effects of BC membranes with that in a different study to deliver berberine hydrochloride or berberine sulfate for oral tablet delivery, and their findings suggest that BC can be utilized as a potential drug carrier with extended-release characteristics (Fig. 9) [87].

It was found that by the inclusion of packed protein film on nanocellulose, hydrophobic solid drug nanoparticles could be attached directly to the surface of nanocellulose, which can enhance the duration of stability for the drug under physiological conditions [88]. Nevertheless, there are some concerns regarding the use of natural nanocellulose for the delivery of pharmaceuticals such as the influence of nanocellulose on the regulation of drug release and drug–nanocellulose interactions [89] and the potential disruption of pharmacological activity or structure [90]. For instance, in a recent study, the surface charges on nanocellulose (TEMPO-oxidized anionic CNF) were found to negatively affect the chemical stability of a model drug, aspirin, and accelerate the drug degradation time [91]. On the other hand, promising data have also been reported for the encapsulation of therapeutics within cellulose-based nanocarriers and their further characterization [92], for instance, the preparation of lutein-encapsulated hydroxypropyl methylcellulose phthalate spherical nanocapsules has been reported to be a feasible approach by using SAS technology, with over 88 % lutein encapsulation yield and <220 nm nanocapsule size [93]. This finding may support the superiority of cellulose-based nanomaterials for use as a potential drug delivery system, since smaller-sized nanoparticles may have high kinetic stability to avoid sedimentation, and their high surface-to-volume ratio may increase the adhesion potential of these substances to tissue surfaces within the body [94].

In recent years, there has been an increased interest in developing doxorubicin-encapsulated cellulose nanoparticles for potential use in anticancer treatment. Yang et al. (2020) developed cellulose-based supramolecular nanoparticles and evaluated their cellular internalization [95]. It was shown that doxorubicin-encapsulated cellulose nanoparticles were taken up into the cells via endocytosis, and a slow release of doxorubicin has been observed for those (19.8 % release within 2 days), while free doxorubicin has been observed to quickly penetrate through cellular/nuclear membranes by passive diffusion [95]. Kumari et al. (2018) developed doxorubicin-encapsulated oxidized cellulose nanoparticles, and the release of doxorubicin was found to be time and pH dependent, such that up to 71.5 % release within 4 days at pH 5.0 has been reported for this system (Fig. 10) [96]. In a very recent study, Gulsu and Yuksektepe (2021) reported the development of doxorubicin-encapsulated

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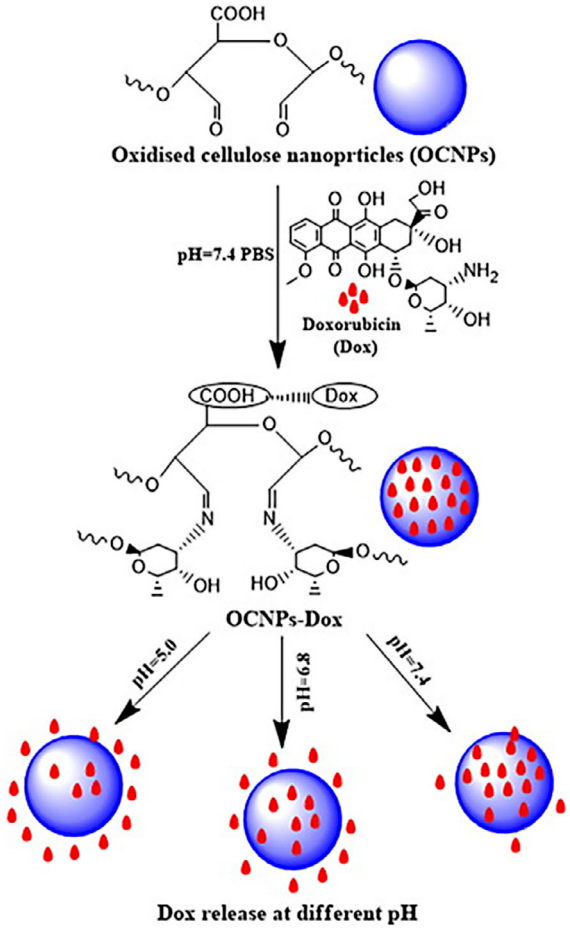

Figure 10. Schematic illustration of doxorubicin loading into OCNPs (upper part) and release of doxorubicin from OCNP-Dox at different pH levels (lower part). Reproduced from [96] with permission from Elsevier.

spherical cellulose nanoparticles, and they evaluated their anticancer potential on the human A549 (human lung adenocarcinoma) cell line [2]. The results indicate that these spherical doxorubicin-encapsulated cellulose nanoparticles are effective on the model cancer cell line, and the nanoparticles have a sustained drug release profile (up to 34 days with 97 % drug release) [2].

Some of the selected key studies for applications of cellulose-based nanomaterials in the therapeutics area are listed in Tab. 2, highlighting the design of these nanomaterials and their application purposes in each subcategory, antibacterial material design and drug delivery.

4 Conclusion

Nanotechnology is a consistently evolving scientific field that continues to produce innovative solutions to address everyday challenges faced by humanity. In recent years, researchers studying in the nanotechnology field have been mostly focused on developing nanomaterials from natural raw materials that are environmentally friendly, biodegradable, and nontoxic. Cellulose is a natural carbohydrate polymer that meets these properties, and nanomaterials from cellulose can be easily manufactured. In this review, we focused on and brought together recent data for biotechnological applications of cellulose-based nanomaterials in wastewater treatment, food packaging, antimicrobial material design, and drug delivery systems. As mentioned in the above sections, cellulose-based nanomaterials are tunable and can be manufactured in divergent shapes and sizes, and for better efficiency, they can be combined with other synthetic/natural polymers, metalized biofilms, metallic nanoparticles, enzymes, proteins, or living organisms (e.g., bacteria and microalgae). These functionalized cellulose-based nanomaterials have great potential to be used particularly in the food and pharmaceutical industries, and they have other potential application areas which are not covered in this review. Nevertheless,

Table 2. A selection of recent studies mentioning applications of CBN for therapeutics in different application areas, antimicrobial material design, and drug delivery.

Application area for CBN	Design of nanomaterials	Applications	References
Antimicrobial material design	– Surface modifications with oxidation, esterification, or etherification – Addition of ammonium compounds – Combination with antibiotics – Combination with metallic nanoparticles such as gold and silver – Combination with enzymes	– Oxidants such as TEMPO bind the surface of nanocellulose, and the provided material can support wound dressing – Production of antibiotics (e.g., ampicillin and gentamycin) containing hydrogels to inhibit the growth of *E.coli, E. faecalis, S. aureus*, and *P. aeruginosa*, which can be utilized in wound dressing – Addition of H_2O_2-producing enzymes to provide antimicrobial efficiency, since H_2O_2 can disrupt bacterial membranes, and low concentrations of H_2O_2 may act on redox-sensitive cell signaling that supports wound healing	[67, 69–71, 75–77]
Drug Delivery	– Bacterial nanocellulose – Cellulose-based supramolecular or oxidized cellulose nanoparticles – Spherical cellulose nanoparticles	– Oral tablet delivery – Anticancer agent (doxorubicin) delivery on model tumor cell lines (e.g., A549 – human lung adenocarcinoma)	[2, 87, 95, 96]

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there might be challenges as well when developing cellulose-based nanomaterials. For instance, nanocellulose needs surface modification in some cases via treatment with harmful and toxic substances, and this results in additional environmental problems. In addition, some antimicrobial cellulose-based nanomaterials contain synthetic and non-environmental additives, which may also cause problems. This problem might be solved via the use of natural plant-based antimicrobial molecules, and fortunately, there is an increased interest in developing greener antimicrobial nanomaterials in recent years. In the future, owing to the eco-friendly and desirable properties of cellulose (e.g., high mechanical strength and tunable physical and chemical properties), it is expected to observe widespread integration of nanocellulose materials across various aspects of human life and environmental sustainability.

Conflicts of Interest

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

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Author contribution

R.S. designed and prepared the schematic figures and contributed to the organization of the manuscript. Both R.S. and O.F.S. wrote the article. O.F.S. supervised the planning and literature survey and got the permissions for republished figures.

Abbreviations

BC	bacterial cellulose
BNC	bacterial nanocellulose
CA	cellulose acetate
CBNs	cellulose-based nanomaterials
CMs	cellulose microfibrils
CMC	carboxymethylated cellulose
CNCs	cellulose nanocrystals
CNF	cellulose nanofiber
CTAB	cetyl trimethylammonium bromide
DDTPPBr	dodecyl-triphenyl phosphonium bromide
EFP	edible food packaging
MCC	microcrystalline cellulose
MFC	microfibrillated cellulose
nCA	non-porous cellulose acetate
pCA	porous cellulose acetate
PHMB	polyhexamethylene biguanide
PET	polyethylene terephthalate
SDS	sodium dodecyl sulfate
SEM	scanning electron microscope
SFMPI	sunflower meal protein isolate
TEMPO	2,2,6,6-teramethylpiperidinyloxy

References

[1] L. L. Lu, W. Fan, X. Meng, L. L. Xue, S. B. Ge, C. Wang, S. Y. Foong, C. S. Y. Tan, C. Sonne, M. Aghbashlo, M. Tabatabaei, S. S. Lam, *Sci. Total Environ.* **2023**, *856*, 158798. DOI: https://doi.org/10.1016/j.scitotenv.2022.158798

[2] A. Gulsu, E. Yuksektepe, *Chem. Sel.* **2021**, *6* (*22*), 5419–5425. DOI: https://doi.org/10.1002/slct.202101683

[3] A. Jeihanipour, M. J. Taherzadeh, *Bioresour. Technol.* **2009**, *100* (*2*), 1007–1010. DOI: https://doi.org/10.1016/j.biortech.2008.07.020

[4] H. T. Phuong, N. K. Thoa, P. T. A. Tuyet, Q. N. Van, Y. D. Hai, *Crystals* **2022**, *12* (*1*), 106. DOI: https://doi.org/10.3390/cryst12010106

[5] S. Rongpipi, D. Ye, E. D. Gomez, E. W. Gomez, *Front. Plant Sci.* **2019**, *9*, 1894. DOI: https://doi.org/10.3389/fpls.2018.01894

[6] R. C. R. Nunes, *Woodh. Pub. S. Compos. S.* **2017**, *75*, 463–494. DOI: https://doi.org/10.1016/B978-0-08-100409-8.00013-9

[7] H. N. Abdelhamid, A. P. Mathew, *Int. J. Mol. Sci.* **2022**, *23* (*10*), 5405. DOI: https://doi.org/10.3390/ijms23105405

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[8] A. Dufresne, *Mater. Today* **2013**, *16* (*6*), 220–227. DOI: https://doi.org/10.1016/j.mattod.2013.06.004
[9] E. Robles, J. Fernandez-Rodriguez, A. M. Barbosa, O. Gordobil, N. L. V. Carreno, J. Labidi, *Carbohydr. Polym*. **2018**, *183*, 294–302. DOI: https://doi.org/10.1016/j.carbpol.2018.01.015
[10] H. M. Gu, X. Gao, H. Zhang, K. L. Chen, L. C. Peng, *Ultrason. Sonochem.* **2020**, *66*, 104932. DOI: https://doi.org/10.1016/j.ultsonch.2019.104932
[11] G. N. Juarez-Luna, E. Favela-Torres, I. R. Quevedo, N. Batina, *Carbohyd. Polym.* **2019**, *220*, 110–117. DOI: https://doi.org/10.1016/j.carbpol.2019.05.058
[12] S. Swingler, A. Gupta, H. Gibson, M. Kowalczuk, W. Heaselgrave, I. Radecka, *Polymers* **2021**, *13* (*3*), 412. DOI: https://doi.org/10.3390/polym13030412
[13] H. Yang, M. N. Alam, T. G. M. van de Ven, *Cellulose* **2013**, *20* (*4*), 1865–1875. DOI: https://doi.org/10.1007/s10570-013-9966-7
[14] D. Trache, A. F. Tarchoun, M. Derradji, T. S. Hamidon, N. Masruchin, N. Brosse, M. H. Hussin, *Front. Chem.* **2020**, *8*, 392. DOI: https://doi.org/10.3389/fchem.2020.00392
[15] K. Missoum, M. N. Belgacem, J. Bras, *Materials* **2013**, *6* (*5*), 1745–1766. DOI: https://doi.org/10.3390/ma6051745
[16] A. Mautner, *Polym.Int*. **2020**, *69* (*9*), 741–751. DOI: https://doi.org/10.1002/pi.5993
[17] A. W. Carpenter, C. F. de Lannoy, M. R. Wiesner, *Environ. Sci. Technol.* **2015**, *49* (*9*), 5277–5287. DOI: https://doi.org/10.1021/es506351r
[18] S. S. Ray, A. O. C. Iroegbu, *ACS Omega* **2021**, *6* (*7*), 4511–4526. DOI: https://doi.org/10.1021/acsomega.0c06070
[19] A. Jamshaid, A. Hamid, N. Muhammad, A. Naseer, M. Ghauri, J. Iqbal, S. Rafiq, N.S. Shah, *ChemBioEng. Rev.* **2017**, *4* (*4*), 240–256. DOI: https://doi.org/10.1002/cben.201700002
[20] J. R. A. Cosme, R. Castro-Muñoz, V. Vatanpour, *ChemBioEng. Rev.* **2023**, *10* (*2*), 112–132. DOI: https://doi.org/10.1002/cben.202200017
[21] L. Valencia, S. Kumar, E. M. Nomena, G. Salazar-Alvarez, A. P. Mathew, *ACS Appl. Nano Mater*. **2020**, *3* (*7*), 7172–7181. DOI: https://doi.org/10.1021/acsanm.0c01511
[22] L. Valencia, E. M. Nomena, S. Monti, W. Rosas-Arbelaez, A. P. Mathew, S. Kumar, K. P. Velikov, *Nanoscale* **2020**, *12* (*29*), 15652–15662. DOI: https://doi.org/10.1039/D0NR02888F
[23] Y. Li, L. Cao, L. Li, C. Yang, *J. Hazard. Mater.* **2015**, *30* (*289*), 140–148. DOI: https://doi.org/10.1016/j.jhazmat.2015.02.051
[24] M. E. Mahmoud, A. E. H. Abdou, M. E. Sobhy, N. A. Fekry, *Int. J. Biol. Macromol.* **2017**,*105* (*1*), 1269–1278. DOI: https://doi.org/10.1016/j.ijbiomac.2017.07.156
[25] Z. Zhang, A. I. S. Ahmed, M. Z. Malik, N. Ali, A. Khan, F. Ali, M. O. Hassan, B. A. Mohamed, J. Zdarta, M. Bilal, *Chemosphere* **2023**, *313*, 137483. DOI: https://doi.org/10.1016/j.chemosphere.2022.137483
[26] S. Jafari, B. P. Wilson, M. Hakalahti, T. Tammelin, E. Kontturi, M. Lundstrom, M. Sillanpaa, *Sustainability* **2019**, *11* (*5*), 1406. DOI: https://doi.org/10.3390/su11051406
[27] A. Tshikovhi, S. B. Mishra, A. K. Mishra, *Int. J. Biol. Macromol.* **2020**, *152* (*1*), 616–632. DOI: https://doi.org/10.1016/j.ijbiomac.2020.02.221
[28] C. Zhang,R. Z. Zhang, Y. Q. Ma, W. B. Guan, X. L. Wu, X. Liu, H. Li, Y. L. Du, C. P. Pan, *ACS Sustain. Chem. Eng.* **2015**, *3* (*3*), 396–405. DOI: https://doi.org/10.1021/sc500738k
[29] S. Ummartyotin, C. Pechyen, *Int. J. Polym. Sci.* **2016**, *2016*, 1–7. DOI: https://doi.org/10.1155/2016/3841410
[30] G. Yuan, M. Prabakaran, S. Qilong, J. S. Lee, I. M. Chung, M. Gopiraman, S. Kyung-Hun, I. S. Kim, *J. Taiwan Inst. Chem. Eng.* **2017**, *70* (*2017*), 352–358. DOI: https://doi.org/10.1016/j.jtice.2016.10.028
[31] Q. Bai, Q. Xiong, C. Li, Y. Shen, H. Uyama, *Cellulose* **2017**, *24*, 4275–4289. DOI: https://doi.org/10.1007/s10570-017-1410-y
[32] X. Huang, X. Zhan, C. Wen, F. Xu, L. Luo, *J. Mater. Sci. Technol.* **2018**, *34* (*5*), 855–863. DOI: https://doi.org/10.1016/j.jmst.2017.03.013
[33] B. C. Pires, F. V. A. Dutra, T. A. Nascimento, K. B. Borges, *React. Funct. Polym.* **2017**, *113* (*2017*), 40–49. DOI: https://doi.org/10.1016/j.reactfunctpolym.2017.02.002
[34] D. Hu, R. Jiang, N. Wang, H. Xu, Y. G. Wang, X. K. Ouyang, *J. Hazard. Mater.* **2019**, *369* (*5*), 483–493. DOI: https://doi.org/10.1016/j.jhazmat.2019.02.057
[35] M. A. Karimi, S. G. Bahoosh, M. Valasek, M. Burkle, M. Mayor, F. Pauly, E. Scheer, *Nanoscale* **2016**, *8* (*20*), 10582–10590. DOI: https://doi.org/10.1039/C5NR08708B
[36] O. F. Sarioglu, O. Yasa, A. Celebioglu, T. Uyar, T. Tekinay, *Green Chem*. **2013**, *15* (*9*), 2566–2572. DOI: https://doi.org/10.1039/C3GC40885J
[37] O. F. Sarioglu, A. Celebioglu, T. Tekinay, T. Uyar, *RSC Adv*. **2015**, *5* (*124*), 102750–102758. DOI: https://doi.org/10.1039/c5ra20739h
[38] N. O. San, A. Celebioglu, Y. Tumtas, T. Uyar, T. Tekinay, *RSC Adv*. **2014**, *4* (*61*), 32249–32255. DOI: https://doi.org/10.1039/C4RA04250F
[39] M. Tomaszewska, B. Bilska, D. Kolozyn-Krajewska, *Int. J. Environ. Res. Public Health* **2022**, *19* (*13*), 8144. DOI: https://doi.org/10.3390/ijerph19138144
[40] H. Yildirim, R. Capone, A. Karanlik, F. Bottalico, P. Debs, H. El Bilali, *J. Food Nutr. Res.* **2016**, *4* (*8*), 483–489. DOI: https://doi.org/10.12691/jfnr-4-8-1
[41] S. S. Ahankari, A. R. Subhedar, S. S. Bhadauria, A. Dufresne, *Carbohydr. Polym.* **2021**, *255*, 117479. DOI: https://doi.org/10.1016/j.carbpol.2020.117479
[42] F. A. G. S. Silva, F. Dourado, M. Gama, F. Pocas, *Nanomaterials* **2020**, *10* (*10*), 2041. DOI: https://doi.org/10.3390/nano10102041
[43] R. K. Gupta, P. Guha, P. P. Srivastav, *Food Chem. Adv.* **2022**, *1*, 100135. DOI: https://doi.org/10.1016/j.focha.2022.100135
[44] P. Mali, A. P. Sherje, *Carbohydr. Polym.* **2022**, *275*, 118668. DOI: https://doi.org/10.1016/j.carbpol.2021.118668
[45] C. Rovera, F. Fiori, S. Trabattoni, D. Romano, S. Farris, *Nanomaterials* **2020**, *10* (*4*), 735. DOI: https://doi.org/10.3390/nano10040735
[46] J. P. de Oliveira, G. P. Bruni, S. L. M. el Halal, F. C. Bertoldi, A. R. G. Dias, E. D. Zavareze, *Int. J. Biol. Macromol.* **2019**, *124*, 175–184. DOI: https://doi.org/10.1016/j.ijbiomac.2018.11.205
[47] J. K. Kim, B. Choi, J. Jin, *Carbohyd. Polym.* **2020**, *249*, 116823. DOI: https://doi.org/10.1016/j.carbpol.2020.116823
[48] W. L. Zhang, Y. Q. Zhang, J. K. Cao, W. B. Jiang, *Int. J. Biol. Macromol.* **2021**, *166*, 288–296. DOI: https://doi.org/10.1016/j.ijbiomac.2020.10.185
[49] V. Katiyar, T. Ghosh, *Nanotechnology in Edible Food Packaging*, Springer, Singapore, **2021**. DOI: https://doi.org/10.1007/978-981-33-6169-0.

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[50] S. Saedi,C. V. Garcia,J. T. Kim, G. H. Shin, *Cellulose*, **2021**, *28* (*14*), 8877–8897. DOI: https://doi.org/10.1007/s10570-021-04086-0

[51] J. Li, X. Wei, Q. Wang, J. Chen, G. Chang, L. Kong, J. Su, Y. Liu, *Carbohydr. Polym.* **2012**, *90* (*4*), 1609–1613. DOI: https://doi.org/10.1016/j.carbpol.2012.07.038

[52] C. U. Maheswari, K. O. Reddy, E. Muzenda, B. R. Guduri, A. V. Rajulu, *Biomass Bioenergy* **2012**, *46* (*1*), 555–563. DOI: https://doi.org/10.1016/j.biombioe.2012.06.039

[53] H. Xie, H. Du, X. Yang, C. Si, *Int. J. Polym. Sci.* **2018**, *2018*, 7923068. DOI: https://doi.org/10.1155/2018/7923068

[54] M. Z. Al-Gharrawi, J. W. Wang, D. W. Bousfield, *Food Packag. Shelf Life* **2022**, *33*, 100895. DOI: https://doi.org/10.1016/j.fpsl.2022.100895

[55] M. Vähä-Nissi, H. M. Koivula, H. M. Räisänen, J. Vartiainen, P. Ragni, E. Kenttä, T. Kaljunen, T. Malm, H. Minkkinen, A. Harlin, *J. Appl. Polym. Sci.* **2017**, 134 (*19*). DOI: https://doi.org/10.1002/app.44830

[56] C. Oktay, L. N. Kahyaoglu, M. Moradi, *Carbohyd. Polym.* **2023**, *319*, 121184. DOI: https://doi.org/10.1016/j.carbpol.2023.121184

[57] T. Almeida, A. Karamysheva, B. F. A. Valente, J. M. Silva, M. Braz, A. Almeida, A. J. D. Silvestre, C. Vilela, C. S. R. Freire, *Food Hydrocolloid.* **2023**, *144*, 108934. DOI: https://doi.org/10.1016/j.foodhyd.2023.108934

[58] M. N. Efthymiou, E. Tsouko, A. Papagiannopoulos, I. G. Athanasoulia, M. Georgiadou, S. Pispas, D. Briassoulis, T. Tsironi, A. Koutinas, *Sci. Rep.* **2022**, *12*, 6935. DOI: https://doi.org/10.1038/s41598-022-10913-6

[59] E. Souza, L. Gottschalk, O. Freitas-Silva, *Recent Pat. Food, Nutr. Agric.* **2020**, *11* (*2*), 154–167. DOI: https://doi.org/10.2174/2212798410666190715153715

[60] H. Shi, L. Wu, Y Luo, F. Yu, H. Li, *Food Biosci.* **2022**, *48*, 101729. DOI: https://doi.org/10.1016/j.fbio.2022.101729

[61] J. Li, F. Zhang, Y. Zhong, Y. Zhao, P. Gao, F. Tian, X. Zhang, R. Zhou, P. J. Cullen, *Polymers* **2022**, *14* (*19*), 4025. DOI: https://doi.org/10.3390/polym14194025

[62] A. J. Sanjari, M. Asghari, *ChemBioEng Rev.* **2016**, *3* (*3*), 134–158. DOI: https://doi.org/10.1002/cben.201500020

[63] A. D. A. Bin Abu Sofian, H. R. Lim, K. W. Chew, P. L. Show, *ChemBioEng Rev.* **2024**, *11* (*2*), 406–425. DOI: https://doi.org/10.1002/cben.202300054

[64] I. Gan, W. S. Chow, *Food Packag. Shelf Life.* **2018**, *17*, 150–161. DOI: https://doi.org/10.1016/j.fpsl.2018.06.012

[65] M. S. Andrade, O. H. Ishikawa, R. S. Costa, M. V. Seixas, R. C. Rodrigues, E. A. Moura, *Food Packag. Shelf Life* **2022**, *31*, 100807. DOI: https://doi.org/10.1016/j.fpsl.2021.100807

[66] M. Moradi, H. Tajik, H. Almasi, M. Forough, P. Ezati, *Carbohydr. Polym.* **2019**, *222*, 115030. DOI: https://doi.org/10.1016/j.carbpol.2019.115030

[67] M. N. F. Norrrahim, N. M. Nurazzi, M. A. Jenol, M. A. A. Farid, N. Janudin, F. A. Ujang, T. A. T. Yasim-Anuar, S. U. F. S. Najmuddin, R. A. Ilyas, *Mater. Adv.* **2021**, *2* (*11*), 3538–3551. DOI: https://doi.org/10.1039/D1MA00116G

[68] L. Morrison, T. R. Zembower, *Gastrointest Endosc. Clin. N. Am.* **2020**, *30* (*4*), 619–635. DOI: https://doi.org/10.1016/j.giec.2020.06.004

[69] J. Li, R. Cha, K. Mou, X. Zhao, K. Long, H. Luo, F. Zhou, X. Jiang, *Adv. Healthcare Mater.* **2018**, *7* (*20*), e1800334. DOI: https://doi.org/10.1002/adhm.201800334

[70] D. Califano, B. L. Patenall, M. A. S. Kadowaki, D. Mattia, J. L. Scott, K. J. Edler, *Biomacromolecules* **2021**, *22* (*2*), 754–762. DOI: https://doi.org/10.1021/acs.biomac.0c01536

[71] M. Li, X. H. Liu, N. Liu, Z. H. Guo, P. K. Singh, S. Y. Fu, *Colloid. Surf. A* **2018**, *554*, 122–128. DOI: https://doi.org/10.1016/j.colsurfa.2018.06.031

[72] N. S. Nemes, C. Ardean, C. M. Davidescu, A. Negrea, M. Ciopec, N. Duteanu, P. Negrea, C. Paul, D. Duda-Seiman, D. Muntean, *Polymers* **2022**, *14* (*4*), 735. DOI: https://doi.org/10.3390/polym14040735

[73] L. Brinkac, A. Voorhies, A. Gomez, K. E. Nelson, *Microb. Ecol.* **2018**, *74* (*4*), 1001–1008. DOI: https://doi.org/10.1007/s00248-017-0985-z

[74] E. Christaki, M. Marcou, A. Tofarides, *J. Mol. Evol.* **2020**, *88* (*1*), 26–40. DOI: https://doi.org/10.1007/s00239-019-09914-3

[75] E. Kaplan, T. Ince, E. Yorulmaz, F. Yener, E. Harputlu, N. T. Lacin, *J. Biomater. Tissue Eng.* **2014**, *4* (*7*), 543–549. DOI: https://doi.org/10.1166/jbt.2014.1198

[76] U. D. Hemraz, E. Lam, R. Sunasee, *Carbohydr. Polym.* **2023**, *315*, 120987. DOI: https://doi.org/10.1016/j.carbpol.2023.120987

[77] S. Shankar, A. A. Oun, J. W. Rhim, *Int. J. Biol. Macromol.* **2018**, *107*, 17–27. DOI: https://doi.org/10.1016/j.ijbiomac.2017.08.129

[78] T. G. Ambaye, M. Vaccari, S. Prasad, E. D. van Hullebusch, S. Rtimi, *J. Environ. Manage.* **2022**, *301*, 113850. DOI: https://doi.org/10.1016/j.jenvman.2021.113850

[79] G. D. Mulder, J. P. Cavorsi, D. K. Lee, *Wounds* **2007**, *19* (*7*), 173–182.

[80] X. M. Song, L. Y. Zhang, Y. Wang, R. Zhao, X. X. Sun, Y. Tian, R. R. Sun, C. H. Hua, R. J. Bai, C. S. Wang, S. S. Gao, *Ind. Crop. Prod.* **2022**, *184*, 115038. DOI: https://doi.org/10.1016/j.indcrop.2022.115038

[81] E. Linley, S. P. Denyer, G. McDonnell, C. Simons, J. Y. Maillard, *J. Antimicrob. Chemother.* **2012**, *67* (*7*), 1589–1596. DOI: https://doi.org/10.1093/jac/dks129

[82] M. Soliman, A. A. Sadek, H. N. Abdelhamid, K. Hussein, *Res. Vet. Sci.* **2021**, *137*, 262–273. DOI: https://doi.org/10.1016/j.rvsc.2021.05.013.

[83] S. J. Eichhorn, A. Etale, J. Wang, L. A. Berglund, Y. Li, Y. Cai, C. Chen, E. D. Cranston, M. A. Johns, Z. Fang, G. Li, L. Hu, M. Khandelwal, K. Y. Lee, K. Oksman, S. Pinitsoontorn, F. Quero, A. Sebastian, M. M. Titirici, Z. Xu, S. Vignolini, B. Frka-Petesic, *J .Mater. Sci.* **2022**, *57* (*10*), 5697–5767. DOI: https://doi.org/10.1007/s10853-022-06903-8

[84] J. K. Jackson, K. Letchford, B. Z. Wasserman, L. Ye, W. Y. Hamad, H. M. Burt, *Int. J. Nanomed.* **2011**, *6*, 321–330. DOI: https://doi.org/10.2147/IJN.S16749

[85] M. C. I. M. Amin, A. G. Abadi, N. Ahmad, H. Katas, J. A. Jamal, *Sains Malays.* **2012**, *41* (*5*), 561–568.

[86] H. Valo, M. Kovalainen, P. Laaksonen, M. Hakkinen, S. Auriola, L. Peltonen, M. Linder, K. Jarvinen, J. Hirvonen, T. Laaksonen, *J. Control. Release* **2011**, *156* (*3*), 390–397. DOI: https://doi.org/10.1016/j.jconrel.2011.07.016

[87] L. Huang, X. L. Chen, T. X. Nguyen, H. R. Tang, L. M. Zhang, G. Yang, *J. Mater. Chem. B* **2013**, *1* (*23*), 2976–2984. DOI: https://doi.org/10.1039/C3TB20149J

[88] R. Dash, A. J. Ragauskas, *RSC Adv.* **2012**, *2* (*8*), 3403–3409. DOI: https://doi.org/10.1039/C2RA01071B

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[89] S. Varjonen, P. Laaksonen, A. Paananen, H. Valo, H. Hahl, T. Laaksonen, M. Ben Linder, *Soft Matter*. **2011**, *7* (*6*), 2402–2411. DOI: https://doi.org/10.1039/C0SM01114B

[90] S. Das, B. Ghosh, K. Sarkar, *Sens. Int.* **2022**, *3*, 100135. DOI: https://doi.org/10.1016/j.sintl.2021.100135

[91] R. Kolakovic, L. Peltonen, A. Laukkanen, M. Hellman, P. Laaksonen, M. B. Linder, J. Hirvonen, T. Laaksonen, *Eur. J. Pharm. Biopharm.* **2013**, *85* (*3*), 1238–1244. DOI: https://doi.org/10.1016/j.ejpb.2013.05.015

[92] A. Gomez-Loredo, J. Benavides, M. Rito-Palomares, *ChemBioEng Rev*. **2015**, *2* (*6*), 393–405. DOI: https://doi.org/10.1002/cben.201500012

[93] H. Jin, F. Xia, C. Jiang, Y. Zhao, L. He, *Chinese J. Chem. Eng.* **2009**, *17* (*4*), 672–677. DOI: https://doi.org/10.1016/S1004-9541(08)60262-1

[94] C. H. Liu, C. T. Wu, *Colloid. Surf. A Physicochem. Eng. Asp.* **2010**, *353* (*2–3*), 149–156. DOI: https://doi.org/10.1016/j.colsurfa.2009.11.006

[95] X. F. Yang, X. Y. Jiang, H. Y. Yang, L. M. Bian, C. Y. Chang, L. N. Zhang, *Carbohydr. Polym.* **2020**, *237*, 116114. DOI: https://doi.org/10.1016/j.carbpol.2020.116114

[96] S. Kumari, B. Ram, D. Kumar, S. Ranote, G. S. Chauhan, *Mater. Sci. Energy Technol.* **2018**, *1* (*1*), 22–28. DOI: https://doi.org/10.1016/j.mset.2018.04.003

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