Journal of
Food Chemistry & Nanotechnology

https://doi.org/10.17756/jfcn.2024-s1-011

Review Article

Open Access

Bacteriocin and Bacterial Cellulose Application in Food Packaging: A Nanotechnology Perspective

Kajal Sharma[1*], Sandeep Kaur[2], Naveen Kumar[3], Arjun Chauhan[4] and Nilakshi Chauhan[5]

[1]*Chitkara School of Health Sciences, Chitkara University, Rajpura, Punjab, India*
[2]*Department of Life Sciences, RIMT University, Mandi Gobindgarh, Punjab, India*
[3]*Chitkara University Research and Innovation Network (CURIN), Chitkara University, Punjab, India*
[4]*Department of Biotechnology, Institute of Applied Sciences and Humanties, GLA University, Mathura, Uttar Pradesh, India*
[5]*Department of Food Science, Nutrition and Technology, CSKHPKV, Palampur, Himachal Pradesh, India*

[*]Correspondence to:
Kajal Sharma
Chitkara School of Health Sciences,
Chitkara University,
Rajpura, Punjab, India.
E-mail: kajal.sharma@chitkara.edu.in

Received: November 24, 2023
Accepted: March 07, 2024
Published: March 11, 2024

Citation: Sharma K, Kaur S, Kumar N, Chauhan A, Chauhan N. 2024. Bacteriocin and Bacterial Cellulose Application in Food Packaging: A Nanotechnology Perspective. *J Food Chem Nanotechnol* 10(S1): S83-S93.

Copyright: © 2024 Sharma et al. This is an Open Access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY) (https://creativecommons.org/licenses/by/4.0/) which permits commercial use, including reproduction, adaptation, and distribution of the article provided the original author and source are credited

Published by United Scientific Group

Abstract

Food industries are growing rapidly in the world, but simultaneously tons of food get wasted every year due to lack of proper packaging and storage. To acquire pathogen free and stable foods many conventional (drying, freezing, chemical preservatives and pasteurization) and non-conventional methods (use of edible coatings on food stuff, bio-preservation, and use of probiotic coating, alternative modified atmospheres, use of essential oils, etc.) are being explored. With advancement in technology, promising food preserving techniques have been emerged and accepted by the public. The food industry is undergoing a transformation because of nanotechnology, which is one of several extremely advanced technologies, including irradiation, high-pressure processing, and hurdle technology. It not only helps in food preservation but also shows an important role in food packaging, processing, and security. In recent times, a lot of research has been carried out to explain the use of nanotechnology along with biomolecules which proves efficient in safe food packaging. This review paper outlines the use of combination of nanomaterials with two major bacterial metabolites namely bacteriocins and bacterial cellulose in food preservation by evidencing different factors which are responsible for food spoilage and make them unhealthy for consumption. Nanotechnology helps bacteriocins and bacterial cellulose to overcome their limitations and raise their scalability at industrial level.

Keywords

Food packaging, Nanotechnology, Bacterial cellulose, Bacteriocins, Food spoilage, Nanomaterials

Introduction

Food becomes unsuitable for human consumption due to metabolic processes which lead to undesirable sensory and quality changes [1]. Deterioration of foods can be caused by the different physical, chemical, and microbial actions. Temperature, pH, oxygen, nutrition, and the presence of different chemicals are all factors that contribute to food spoilage [2]. The microbial spoilage of foods has caused a greater concern than any other form as the bacteria speedily colonizes, increases in population, and generates toxins and offensive chemicals in foodstuffs. This microbial deterioration is typically manifested by changes in appearance, texture, color, and flavor, as well as slime development. The appearance includes color changes, the development of gas packets, and microbiological growth, particularly mold growth [3]. The impact of spoilage due to micro-organisms on sensory and health qualities of food depends on whether the spoilage is on the surface or inside the food [4, 5]. From ancient times, people have used different kinds of

methods to prevent the spoilage of food. Drying, refrigeration and fermentation of food products were the conventional methods of preservation while the modern methods include atmosphere controlled, canning, pasteurization, freezing, irradiation, and the addition of chemical agents [6]. Despite, addition of some chemical preservatives is harmful to humans for instance sulphur dioxide is responsible for irritation in bronchial tubes in asthma patient and nitrites which have been implicated as carcinogens [7].

Unfortunately, the direct addition of some antimicrobial compounds can cause the reduction of active compounds' activity due to the intricacy of food components and strong flavor of some agents, it may change the organoleptic characteristics of foods. Therefore, a possible method to improve antimicrobial effectiveness and circumvent the problem of direct addition is to encapsulate antimicrobial chemicals into packaging matrices [8]. Recently, consumer demand for natural foods, changes in industrial procedures to obtain high-moisture food products, and research on emerging stress factors application such as high pressures, the development of readily available foods with a longer shelf life, and changes in selling practices have all aided in the development of novel and/or superior packaging materials. Consequently, active, intelligent, and edible films and coatings (some time named "safe-to-eat packaging" from plant [9] is developed to overcome the problems related to the food spoilage [10]. Interestingly, many microorganisms and their metabolites like bacteriocin have been used in the production of edible coatings or films which proved to be helpful in elimination of spoilage causing microbes along with increase in shelf-life and quality of foods. Though food preservation by use of bacteriocin-incorporated films is now the most acceptable technique, still, there were some limitations. Eventually, the nanotechnology application in the food sector has resolved almost all issues related to packaging.

Nanotechnology is a technique which involves using materials in the size range of 1 - 100 nm for the management and reformation of such materials, devices, and systems at atomic, molecular, and macromolecular scale to acquire a new system with more advanced properties and novel functional applications [11]. The idea of nanotechnology and nanoscience was introduced by American physicist and Nobel prize laureate Richard Feynman in the year 1959. He described the process of manipulating and controlling atoms and molecules at individual level. After a period of more than 10 years, Professor Norio Taniguchi coined the term 'nanotechnology' and defined it as the process of separation, consolidation, and deformation of materials by one atom or one molecule [12, 13]. The global nanotechnology industry will develop at a compound annual growth rate of 18.1% over the next few years, reaching a market value of $173.95 billion by 2025, according to business wire research [14]. According to Robin [15] "nanotechnology is going to pave the way for a revolution in materials, information and communication technology, medicine, genetics and other fields as commercialization potential is driving innovation from the research laboratories into real world markets." Nanoscale science, engineering, and technology include nanoscale imaging, measurement, modelling, and matter manipulation.

Due to their high surface-to-volume ratio materials at the nanoscale level exhibit unique physical and chemical properties in comparison to their macroscopic forms [16]. Additionally, it is feasible for quantum effects to manifest at the nanoscale [17]. Nanoparticles improve mechanical properties of common materials by forming an intragranular or intergranular structure [18]. Nonetheless, nanomaterials are highly specific in their function and provide the excellent integration of technology and biological systems that was not available in the past years [19]. Due to these extraordinary characteristics of nanomaterials, nanotechnology is regarded as an appropriate approach for different applications such as catalysis, imaging, medical applications, energy-based research, and environmental applications [20]. Furthermore, in food industries, nanotechnology ensures the food quality as well as assesses the food safety and controls the delivery of nutrients by the help of two most important applications, specifically nanosensors and nanostructured ingredients in different food items. Apart from this, nanotechnology can be used for molecular synthesis of food [21]. So, nanotechnology will play an important role in food development, processing, and packaging in the following years.

Edible coatings are mainly composed of bio-based polymers such as hydrocolloids, polysaccharides and proteins that are obtained from plants, animals, and microorganisms. They are used to protect food against mechanical damage caused by impact, pressure, vibrations, and other mechanical forces [22]. Thus, edible coatings not only maintain the quality of food items but also a source of biodegradable packaging as these films or coatings reduce the synthetic packaging [23]. Although both edible coatings and films possess a thin layer of edible material. However, edible film is a performed thin layer that can be applied on or between food components while the former formed as a coating on a food product. Moreover, the edible coating involves immersion (in liquid matrix), spraying, spreading, or brushing over foods whereas the foodstuffs are covered by solid sheets when edible film is used as an active coating. The nature of edible film is self-standing and edible coating is adhering to the food surface [24]. According to the findings of the various studies, edible film had a thickness of 0.18 to 0.24 mm or 40 and 50 μm [25, 26].

Various microbes such as *Campylobacter*, *Escherichia coli*, *Salmonella*, *Staphylococcus aureus*, *Bacillus cereus*, *Clostridium perfringens*, and *Aspergillus niger* are pathogenic in nature may cause harm to consumer health, therefore, contribute to food borne illness [27]. The eco-friendly packaging system provides an additional help for food preservation as edible films are also the carrier of antimicrobial agents. They have numerous benefits as compared to traditional coatings in terms of better spreading; solubility and diffusivity as well as they are helpful in regulating the moisture content and permeability of gas in foods [24]. Likewise, they also enhanced the functionalities of food products that include addition of antioxidants, antibrowning agents and nutrients that were not present in original food for human consumption.

The ability for the introduction of living microorganisms into edible films and coatings creates new prospects and challenges in food production [28]. Though China used the active

packaging such as oranges and lemons covered with waxes to avoid the water loss during transportation and storage in the 12th century, but "yuba" is the very first edible film that was formed in Japan in the early 15th century by utilizing soymilk proteins that involved the air drying of proteins after boiling [29]. Later, larding (use of lards and fats) was introduced in England to increase the shelf life of meat products. Presently, various commercial edible coatings are developed to prevent the spoilage of different foods that includes fruits, vegetables, processed foods, seafood, coating of nuts and many more [30]. The milestone stage in development of ideal edible films is use of living microbes as well as their metabolites including bacteriocidal incorporated films that fulfil the consumer demands as fresh and healthy food is now available to them. Meanwhile, the introduction of nanotechnology also enhanced the functional properties of foods and stability of complex food systems having such edible coatings in a much better way.

Bacteriocins

Bacteriocins are produced by the extracellular secretion of various Gram-positive and Gram-negative bacteria that are synthesized by ribosomes in the form of peptides possessing antimicrobial activity [31]. Bacteriocins can kill or suppress bacterial strains that are closely related or unrelated to the bacterium produced, but due to unique immunity proteins, they will not harm the bacteria themselves. Many recent studies have isolated and identified bacteriocins for use in food technology, with the purpose of extending food shelf life, treating bacterial illness and cancer therapy, and preserving human health. Bacteriocins may potentially become a possible pharmacological candidate for replacing antibiotics in the treatment of multidrug-resistant infections in the future. By preventing the growth of pathogenic bacteria, they can serve as natural food preservatives and improve food safety [32, 33]. Due to heat stability, high pH tolerance and proteolytic behavior, bacteriocins are used as food preservatives. Because of thermal constancy and pH tolerance, bacteriocins can withstand heat and acidity/alkalinity of food during storage conditions [34]. As bacteriocins can be degraded by gastrointestinal proteases and do not cause any harm to human health, i.e., generally recognized as safe having generally regarded as safe (GRAS) status [35]. They show antimicrobial activity by interfering in cell wall synthesis, DNA synthesis, protein synthesis as well as disruption of membrane structure [36].

Classification of bacteriocins

Klanenhammer was the first author who proposed bacteriocin classification. During past times, different classifications of bacteriocins are described [35]. Bacteriocins from lactic acid bacteria can be classified based on biochemical and genetic composition [37]. The occurrence of sulfide (like lanthionine) and disulfide bonds play a major role in classifying the bacteriocins into different groups as well as they also determine their activity spectrum. Moreover, division of main classes into subclasses also depends on various factors including molecular mass, thermostability, enzymatic sensitivity, presence of post-translational modified amino acids, and mode of action [38]. Some authors described four classes of bacteriocins. Out of which one class has cyclic peptides that include bacteriocins namely, lactocin 27 and leuconocin S, but there is no more information about this class [39]. Apart from this, bacteriocins from Gram-negative bacteria are also divided into two categories: (a) high molecular mass modular proteins (30 - 80 kDa) known as colicins and (b) low molecular mass peptides (1 - 10 kDa) termed microcin's. Colicins bacteriocins are produced by *E. coli*, serve as a model system for investigation of bacteriocin structure-function relationship, genetic organization, and their ecological role. Host regulatory mechanisms (such the Si Opus Sit system), which are involved in many bacteria's response to DNA damage, mediate their expression. Microcin's are hydrophobic peptides that are highly stable and are formed in response to stress conditions like nutritional shortage [40]. The detailed classification system for bacteriocins from Gram-positive bacteria is described in table 1.

Among the different classes of bacteriocin, class I and class IIa are widely used in food preservation. Nisin is produced by *Lactococcus lactis* subsp. lactis and it has been used from long time, against Gram-positive bacteria that are considered as food borne pathogens and spoilage agents such as lactic acid bacteria, vegetative pathogens like *Listeria*, *Staphylococcus*, *Mycobacterium*, and spore forming bacteria includes *Bacillus* and *Clostridium* [41]. Nisin is also approved by United States Food and Drug Administration (FDA) as a food preservative, and nisin is used as a food additive in more than 45 countries [42]. It is commercially sold as Nisaplin™, a natural food protectant. Nisin is commonly used in canned food and dairy products [43]. Similarly, pediocin which belongs to class IIa, and produced by *Pediococcus acidilactici* has GRAS status. They are not only active against food borne pathogens such as *Listeria monocytogenes* [44] but also play a beneficial role in health ailments like cancer [45]. Class I (modified peptides, lantibiotics), class II (unmodified peptides, non-lantionine), and class III (large proteins, heat unstable) of the Gram-positive bacteriocins are the three main categories [46].

Bactericidal-nanoparticles systems

The use of nanoparticles along with bacteriocin has proved much effective in betterment of their antimicrobial properties and certain demerits of bacteriocins for instance narrow antimicrobial range, high dose of bacteriocin, lower yield and susceptibility to proteolytic enzymes have been improved with the aid of nanotechnology. Regarding the food sector, the interaction of bacteriocins with nanoparticles significantly increases the antimicrobial spectrum of the former [47]. Nanoparticles when meet the pathogenic bacteria cell surface, they result in various structural changes and noticeably disrupt necessary cell functions like permeability, causing the formation of pits and gaps, depressing the action of respiratory chain enzymes to cause bacterial cell death [48]. Nanomaterials help to increase the stability of bacterial antimicrobial peptides. To quote an example, the antibacterial activity of bacteriocin obtained from *Enterococcus faecium* increased by 50% when immobilized onto cellulose nanocrystals. This is a resourceful method of producing antibacterial nanofillers for food packaging and biocomposites applications [49]. Nonetheless, different methods have been adopted to conjugate these antimicrobial peptides with nanoparticles such as bacteriocins are encapsulated in nanoliposomes and these can

Table 1: Classification of bacteriocins from Gram-positive bacteria.

Bacteriocin	Class I (Lantibiotics)	Class II (Non-lantibiotics)	Class III (Large proteins)
Common features	Post-translationally modified peptides, containing amino acids, such as lanthionine and B-methyllanthionine, and other dehydrated amino acids. Their molecular weight is < 5kDa.	They are small, heat-stable, do not contain lanthionine. Size ranges from 30 to 60 amino acids with molecular weight < 10 kDa.	This group contains heat-labile peptide antibiotics; molecular mass is more than 30 kDa. Their N-terminus acts as a catalytic domain whereas C-terminus provides the target recognition site.
Subclasses	Type A lantibiotics (linear structure and have 21 to 38 amino acids), positively charge peptide, such as nisin.	Class IIa bacteriocins are characterized by conserved amino-terminal sequence (YGNGVXaaC). They are antilisterial pediocin like bacteriocins.	Group A contain lytic enzyme like enter lysin A.
		Class IIb consists of two different unmodified peptides like lactacin F.	
		Class IIc bacteriocins are cyclic bacteriocin, usually cationic, relatively hydrophobic, for e.g., carnocyclin A.	
	Type B lantibiotics (globular structure and can have up to 19 amino acids), can be negatively charged or neutral such as subtilosin A.	Class IId bacteriocins are linear, single peptide bacteriocins which need lipid or carbohydrate moieties for functioning.	Group B are non-lytic protein like helveticin J.
		Class IIe bacteriocins are non-ribosomal siderophore type, having post-translational modifications at serine rich C terminal region like microcin E492.	

be conjugated as well as interacted with chitosan and metallic nanoparticles, respectively [50].

Many of the bacteriocins are mostly used in the medical and food industry due to their beneficial properties. Nisin is the most popular bacteriocin which is not only used in the medical field, but it also has great impact on production and preservation of different food stuffs. Nisin and its combination of different nanomaterials will be discussed in the upcoming section. Except nisin, the nanoencapsulation of pediocin produced by *Pediococcus acidilactici* carried out by the method named as micro fluidization, had been studied for the effect of pH on the kinetics of release of pediocin and its antibacterial activity against *Listeria innocua* [51]. Similarly, sakacin-A possesses the antiliteral activity against *L. innocua* when nanostructured in cellulose nanofibers [52]. Moreover, the bacteriocin immobilized onto cellulose nanocrystals showed improved antibacterial activity [49]. Apart from this, a bacteriocin from *Bacillus sonorensis* MT93, named sonorensin was found to be affected against food-borne pathogens such as *S. aureus* and *L. monocytogenes* by increasing membrane permeability [53].

Nisin-nanomaterial/nanoparticles loaded packaging films

Nisin-containing nanocarriers can function as an antimicrobial agent in food formulations and active packaging. Furthermore, nano formulation plays an important role in functional properties of nisin [54]. Nanoemulsion of nisin, found to be effective against potential food borne pathogen *L. monocytogenes* [55]. Moreover, a film based on nanocellulose fibers which are prepared from sugarcane bagasse and blend with nisin does not only exhibit good oxygen barrier and antimicrobial activity against *L. monocytogenes* but also the concentration of nisin significantly influence the mechanical and optical properties [56]. The combination of bacteriocin with gold nanoparticles significantly increases the antibacterial activity which is a beneficial approach for the development of packaging material [57]. Additionally, nisin loaded pectin nanoparticles also possess antimicrobial potential but their activity is not independent of the type of biopolymer [58].

It was demonstrated that nisin containing carbohydrate nanoparticles showed antilisterial activity more effectively as compared to nisin solution. Phytoglycogenoctenyl succinate, an amphiphilic negatively charged carbohydrate nanoparticle was utilized to produce oil-in water emulsion for delivering nisin which also helps to retain bacteriocin activity during storage [59]. Nisin anchored cellulose films have excellent properties which include transparent properties, barrier properties against oxygen, thermal stability together with antimicrobial activity against *Alicyclobacillus acidoterrestris* for a longer period [60]. Liposomes were co-encapsulated with nisin, and garlic extract reported to hinder the growth of *L. monocytogenes*, *S. aureus*, *E. coli* and *Salmonella enteritidis* in milk [61]. In another study, it was suggested that magnesium oxide nanoparticles together with nisin distort and injure the cell membrane, causing leakage of intracellular contents and finally bacterial cell death [62]. The combination of nisin with polylactic acid and allylisothiocyanate effectively inactivates the growth of *Salmonella* in liquid egg white [63]. Moreover, the combination of copper oxide nanoparticles in nisin also

reduces the pathogenic bacteria in milk by causing significant changes in cell morphology and on membrane integrity [64]. Various nanomaterials are used for enhancing the antibacterial activity and delivery of nisin which are listed below in table 2.

Nanomaterial/nanoparticles provide the effective delivery of nisin, protect it from interacting with food components and degradation caused by enzymes and increase efficacy during storage period [72]. Thus, nanotechnological approaches or nano delivery systems like lipid, carbohydrate, metal, and polymer-based nanoparticles help the bacteriocin to gain better stability and broader antimicrobial spectrum. Moreover, the nature of interaction between these peptides and nanomaterials needs to be clarified [73].

Bacterial nanocellulose

Bacterial nanocellulose, also called bacterial cellulose, is pure cellulose without the presence of pectin and lignin, synthesized extracellularly by some acetic acid bacteria and it is generally formed by glucose monomer. After the secretion of glucose chain protofibrils via bacterial cell wall, these structures combined to form nanofibrils cellulose ribbons. A constant 3D cellulose network made of these ribbons has a high degree of mechanical potency, crystallinity, polymerization, and water retaining capacity [74]. Due to these properties, bacterial cellulose is widely used in electronics, cosmetics, medicine, and food industries [75]. Nonetheless, being a dietary fiber, bacterial cellulose is approved as GRAS food by FDA [76]. Addition of bacterial cellulose in food products results in better dispersion and suspension stability as well as it helps to maintain shape so that consumers enjoy the feeling of fullness in the mouth [77]. Consequently, bacterial cellulose is also used in the production of edible films.

There are two nanostructures of bacterial nanocellulose namely: bacterial cellulose nanocrystals and bacterial cellulose nanofibrils [78]. The length of bacterial nanocellulose nanofibers is near about 100 µm and diameter is approximately 100 nm while the ribbons made up of bundles of cellulose microfibrils have diameter between 2 - 4 nm [79]. Almost every kind of molecule can be integrated within its ultrafine nanofibrous network to prepare the materials with diverse characteristics for using them in different fields. For this reason, bacterial nanocellulose nanocomposites having smart and active properties are used in active and intelligent packaging of foodstuffs [80]. Bacterial cellulose nanocrystals can be obtained by two common methods which include acid hydrolysis with H_2SO_4/HCl and enzymatic hydrolysis with cellulose [81].

The bacterial cellulose nanocrystals functions equally as an emulsion stabilizer and a reinforcement agent [82]. Additionally, bacterial cellulose not only used as thickening, gelling and stabilizing agent but also these cellulosic nanocomposites replaced the excessive use of petroleum-based synthetic and non-biodegradable packaging materials that harm the environment [83, 84]. Bacterial cellulose is utilized as a nutritious dietary supplement for those with gastrointestinal illnesses, obesity, cardiovascular diseases, and diabetes in addition to helping to build edible antibacterial films. Moreover, it may help to reduce the use of chemical preservatives and plastic packaging in foods by offering eco-friendly durable packaging [85]. Apart from this, bacterial cellulose has potential applications in the food industry such as additive ingredients, delivery systems, raw food materials, enzymes, and cell immobilization [86].

Physical properties of bacteriocin containing nano compounds

Properties of bacteriocin itself and of its blends and composites have been investigated. Bacteriocin is a special polymer because of its high purity, high degree of crystallinity, and great capacity for absorption and retention. What's more, it does not have any toxic effect and it is a biodegradable polymer that is inert to human metabolism [77]. Incorporation of lignin and cellulose nanocrystals is reported to enhance the

Table 2: List of nanostructured nisin.

Nanomaterial containing nisin	Targeted organism/properties	Ref.
Solid lipid nanoparticles	Bacteriocin showed sustained release rate from nanoparticles. *L. monocytogenes* and *Lactobacillus plantarum*	[65]
Phosphatidylcholine liposome	Antimicrobial in action	[65]
Gelatin and casein films containing nisin-loaded liposome and halloysitenanoclay	*L. monocytogenes, Bacillus cereus,* and *Clostridium perfringens*	[66]
Nisin loaded liposome nanoparticles	*L. monocytogenes* and *S. aureus*	[67]
Poly (lactic acid) having cellulose nanocrystals	Antimicrobial nanocomposite target *L. monocytogenes*	[65]
Nanocellulose	*S. aureus* and *Bacillus subtilis*	[65]
Bacterial cellulose nanocrystals	Meat spoilage lactic acid bacteria, may use as reinforcing agent in active packaging	[68]
Gelatin nano fibers	*L. monocytogenes*, *L. plantarum* and *S. aureus*	[65]
Nanocellulose	*S. aureus* and *B. subtilis*	[65]
Chitosan nano-gel/emulsion having essential oil	*E. coli* O157:H7	[69]
Agar film containing nisin and silver nanoparticles	*Pseudomonas fluorescens* and *Fusarium moniliforme*	[70]
Gold nanoparticles	*Micrococcus luteus*, *B. cereus*, *S. aureus* and *E. coli*	[71]

activity of bacterial cellulose nanocomposite films in terms of its tensile and barrier properties. Moreover, the presence of lignin provides brown color and opacity to the film, making it possible to produce the films with ultraviolet (UV)-absorbing and antioxidant properties which are helpful in packing of the food products susceptible to lipid oxidation. It was evaluated that bacteriocin coatings possess outstanding UV-barrier characteristics. These UV-barrier properties remained unaffected by water molecules [87, 88]. Similarly, a combination of nanofibrils and nanocrystals of bacterial cellulose could be used as potent films for food packaging. It was observed that nanocrystals significantly increase the tensile strength and elongation of break, decrease the water vapor permeability and enhanced water resistance [89]. The enhancement of these properties was also observed when bacterial cellulose nanofibrils were supplied with cashew gum [83]. Further, the integration of bacterial cellulose nanofibrils with zein nanoparticles significantly improved the thermal stability of films [90]. Additionally, the nanocomposite films containing hydroxypropyl methyl cellulose reinforced with bacterial cellulose nanocrystals and silver nanoparticles had been noticed to possess excellent mechanical properties [91]. Moreover, a combination of bacterial cellulose/polyvinylpyrrolidone/carboxymethyl cellulose provides better mechanical, optical, and biodegradable properties and extends the shelf life of food products like vegetables and meat [92].

Bacterial cellulose as carrier (matrix) in nanocomposites

Antimicrobial food packaging is the most advanced feature of food technology. Bacterial cellulose itself does not have any antimicrobial activity but it is used to incorporate many antimicrobial compounds as it provides controlled release of impregnated material. Bacterial cellulose incorporated with ε-polylysine utilized for increasing the shelf-life of food products as it shows bacteriostatic and bactericidal activity against several Gram-negative and Gram-positive bacteria [93]. Equally, the combination of bacterial nanocellulose with lactoferrin showed high antimicrobial activity against *E. coli* and *S. aureus* [94]. Bacterial cellulose films incorporated with lauric acid inhibit the growth of *B. subtilis* [95]. Moreover, nanocomposite films containing chitosan and silver nanoparticles possess strong antimicrobial activity against food borne pathogens like bacteria and fungus [96]. Bacterial cellulose together with zinc oxide nanoparticles act as an appropriate food packaging material by the controlled release of antimicrobial agents [97]. Similarly, it was noticed that silver nanoparticles/bacteriocin nanocomposites protect the foods against microbial spoilage for 30 days, being better than commercial polythene bags which cause the spoilage of food within 15 days [98]. Nonetheless, bacterial cellulose films having encapsulated *Lactobacillus acidophilus* exhibited anti-fungal properties as they prevent growth of *Aspergillus niger* in cheese without affecting the other characteristics [99]. Similarly, bacterial nanocellulose film impregnated with postbiotics of *L. plantarum* remarkably reduces the growth of *L. monocytogenes* as well as other mesophilic and psychrophilic microorganisms in meats [100]. Fahim et al. [73] used layered double hydroxide nanoparticles and fractional factorial design to increase the yield and antibacterial activity duration of the bacteriocina-vicin-A. Increased antibacterial activity against *Lactobacillus sakei* LMGT 2313 due to the nanocomposite of avicin-A and layered double hydroxide remained longer (at least 24 days) than free avicin-A (6 - 15 days) [101]. Also, the antimicrobial activity of plantaricin-silver nanocomposite showed 99.2% more antimicrobial activity and enhanced stability up to 60 days (Figure 1) [102].

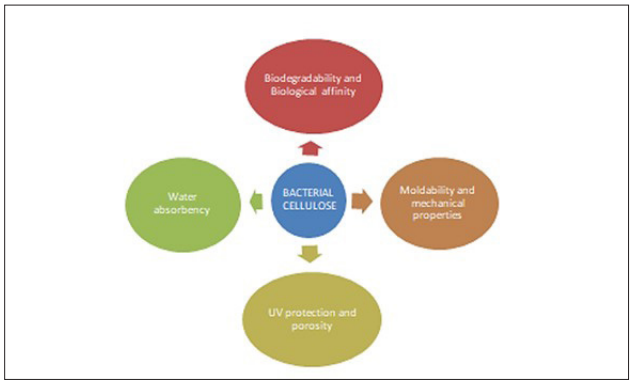


Figure 1: Various properties of bacterial cellulose.

Bacterial cellulose in intelligent and active food packaging

Bacterial cellulose also plays an important role in intelligent food packaging. There are numerous packaging materials based on nanocellulose that have been created and shown to have the potential to be used as active and intelligent food packaging materials [80]. It provides a better matrix for the immobilization of pigment like anthocyanins which acts as pH sensor for the milk and helps to distinguish spoiled and fresh milk [103]. Bacterial nanocellulose plus methyl red can be used as a gas sensor for volatile amines [104]. Similarly, bacterial nanocellulose with poly (Sulfobetaine methacrylate) (zwitterions films) not only prevent food from harmful effects of UV radiation but also act as a protonic-conduction humidity sensor [80]. Bacterial cellulose is used in active food packaging when combined with poly (3-hydroxybutyrate) activated with clove essential oil [83]. Apart from this, bacterial cellulose incorporated with *Scophularia striata* extract could be used as controlled release antioxidant food active packaging [105].

Advantages of the nanoencapsulated particles use in food packaging

The encapsulation technique is based on the coatings' ability to embed themselves in the structural matrix, creating a microenvironment that may regulate interactions between internal and external components [106] while the definition of nanoencapsulation as a method that makes use of nanocomposite, nano emulsification, and nano-structuration techniques to pack substances in miniature [107] and electrospinning/electrospraying. Nanomaterials, because of their fine particle size range between 1 nm to 100 nm possess myriad properties namely high surface area, high reactivity, high strength, and ductility [108]. Due to these factors, packaging materials can be engineered using nanotechnology to create the necessary barriers and mechanical properties to store the bioactive compounds and to enhance their intended activities [109]. These methods enable the integration of hydrophilic and lipophilic compounds with antibacterial and antioxidant activity that can release during storage, extending the shelf life of various

foods such as whole and freshly cut fruits and vegetables, nuts, seeds, and cheese [110]. In fact, nanoencapsulation of food ingredients improve the dispersibility in foods together with beverages and enhance their bioavailability by exhibiting superior dose-dependent functionalities and mask dysgeusia to reduce the unpleasant effect on mouthfeel [111].

In the food industry, different nanotechniques are being used that include nanoemulsions, nanolaminates, nanocomposite and nanosensors. Nanoemulsions are nanoformulations with advanced structural and functional properties which can be used for the encapsulation of bioactive substances, and they also ensure the effective delivery of coloring and flavoring food agents as well as antimicrobials. Additionally, the nanoemulsion coatings do not only minimize the moisture loss and gaseous exchange but also remain unaffected by physico-chemical factors like heat and pH [112]. Nanoemulsion formulations increase the stability and solubility of bacteriocin in media. Maté et al. [113] studied the efficacy of D-limonene and nisin based nanoemulsion on *L. monocytogenes*. D-limonene and nisin collectively in form of nanoemulsion found more effective in checking the growth of *L. monocytogenes* at least three log cycles within the first 90 minutes. Equally, nanolaminate is another nanoscale technique that is made up of two or more layers of material with nanometer dimensions. It is also used in the preparation of edible films based on polysaccharides, proteins, and lipids. However, these coatings have low properties due to which researchers are trying to improve their functionality [21]. Nanocomposites are materials with at least one dimension smaller than 100 nm. They improve mechanical and thermal properties of packaging material to a great extent [114]. Apart from this, nano sensing is an emerging technology which has specific properties that includes detection of taste, smell, vitamins, adulterant, pathogenic microbes, and toxins produced by contaminants in foods (Table 3) [115].

Food packaging is considered as the major application of nanotechnology in the food industry. Reynolds demonstrated that about 400 - 500 nano-packaging foodstuffs are commercially accessible, and nanotechnology is estimated to be applied in the production of entire food packaging within the next generation [122]. Furthermore, nanoencapsulation provides active packaging through nanostructures that are loaded with active components like flavors or aromas with controlled release to food [123]. Nanoformulations are not only active against food spoilage microbes, but they efficiently reduce the pathogenic microbes on food articles. In fact, in future packaging, nanoencapsulation will play a vital role in providing anti-rodent and insect repellent activities if bioactive compounds having such properties are encapsulated in foods [124]. Nanocomposites lower the packaging waste linked with processed products and due to addition of nanoparticles heavy packages can be turned into light weight packing [125]. The bio-nanocomposite films and edible coatings help to prevent the color changes, respiration rate, and loss of weight, thus extending shelf life [126]. Nonetheless, the nano-delivery system provides fresh as well as healthy foods to consumers. All in all, the use of nano-films not only makes it possible to prevent food from deterioration but also it has had a great impact on the food industry in terms of economic growth.

Conclusion

Nanotechnology is the best way to prevent the foodstuff industries from going for a longer period as well as in harsh storage conditions. Interestingly, its use with bacteriocins and bacterial cellulose gives more attractive and healthy features to food products. This approach will be useful in upcoming years for producing stable food as it brings evolution in food preservation, packaging, and processing. Moreover, this practice limits the use of harmful chemicals in foods and extends the shelf-life without the loss of nutrients. Nonetheless, it is a very costly and complicated process to produce nano-food

Table 3: Benefits of four most accepted nanotechniques involving in food industry.

Name of nanotechnique	Benefits	Ref.
Nanocomposite	Improve durability and barrier properties. Temperature and flame resistance. Improve process ability due to lower viscosity. Abrasion resistance. Reduce the growth of food spoilage microorganism for example nanocomposite incorporated with silver.	[116, 117]
Nanoemulsion	Retains flavors or aroma. Prevent oxidation and enzymatic reactions. Thermally stable as compared to conventional emulsions. Easy to digest. Improve texture, high optical visibility. Increase the bioavailability of phytochemicals such as carotenoids and polyphenols that have several health benefits.	[118]
Nanosensors	Enhanced food security. Detect pathogens, toxins, adulterant, vitamins, dyes, taste, and smell. Allow the monitoring of foods in different phases namely, production, processing, distribution, and consumption.	[115, 119, 120]
Nanolaminates	Prevent food from gases, humidity, and lipids. Improve texture as well as act as carrier of colors, flavors, antioxidants, nutrients, and antimicrobials. Used in packing of chocolates, candies, fruits, vegetables, meat products, and bakery products.	[121]

packaging, also skilled personnel are required to manufacture the nano-foods so that the right concentration of nanomaterials should be used to protect food from toxicity.

Acknowledgements

None.

Conflict of Interest

None.

References

1. FRI Briefings: Microbial food spoilage: losses and control strategies.
2. Amit SK, Uddin MM, Rahman R, Islam SMR, Khan MS. 2017. A review on mechanisms and commercial aspects of food preservation and processing. *Agric Food Secur* 6(1): 51. https://doi.org/10.1186/s40066-017-0130-8
3. Pitt JI, Hocking AD. 2009. Fungi and Food Spoilage. Springer, New York.
4. Hammond ST, Brown JH, Burger JR, Flanagan TP, Fristoe TS, et al. 2015. Food spoilage, storage, and transport: implications for a sustainable future. *BioScience* 65(8): 758-768. https://doi.org/10.1093/biosci/biv081
5. Baron F, Gautier M. 2016. Microbial Spoilage. In Jeantet R, Croguennec T, Schuck P, Brulé G (eds) Handbook of Food Science and Technology 1: Food Alteration and Food Quality. John Wiley and Sons.
6. Desrosier NW, Singh RP. 2018. Food Preservation. Encyclopedia Britannica.
7. Abdulmumeen HA, Risikat AN, Sururah AR. 2012. Food: its preservatives, additives and applications. *Int J Chem Biol Sci* 1: 36-47.
8. Rawdkuen S. 2018. Edible Films Incorporated with Active Compounds: Their Properties and Application. In Var I, Uzunlu S (eds) Active Antimicrobial Food Packaging. IntechOpen.
9. Packaging Safe Enough to Eat? [https://packagingeurope.com/packaging-safe-enough-to-eat/2669.article] [Accessed March 11, 2024]
10. Campos CA, Gerschenson LN, Flores SK. 2011. Development of edible films and coatings with antimicrobial activity. *Food Bioprocess Technol* 4(6): 849-875. https://doi.org/10.1007/s11947-010-0434-1
11. Roco MC, Mirkin CA, Hersam MC. 2011. Nanotechnology research directions for society needs in 2020: summary of international studies. *J Nanopart Res* 13: 897-919. https://doi.org/10.1007/s11051-011-0275-5
12. Roco MC. 2023. National nanotechnology initiative at 20 years: enabling new horizons. *J Nanopart Res* 25: 197. https://doi.org/10.1007/s11051-023-05829-9
13. Bayda S, Adeel M, Tuccinardi T, Cordani, M, Rizzolio F. 2020. The history of nanoscience and nanotechnology: from chemical-physical applications to nanomedicine. *Molecules* 25(1): 112. https://doi.org/10.3390/molecules25010112
14. Ciambelli P, Guardia GL, Vitale L. 2020. Nanotechnology for green materials and processes. *Stud Surf Sci Catal* 7(179): 97-116. https://doi.org/10.1016/B978-0-444-64337-7.00007-0
15. Robin AM. 2012. Common nanomaterials and their use in real world applications. *Sci Prog* 95(1): 1-22. https://doi.org/10.3184/003685012X13294715456431
16. Singh T, Shukla S, Kumar P, Wahla V, Bajpai VK, et al. 2017. Application of nanotechnology in food science: perception and overview. *Front Microbiol* 8: 1501. https://doi.org/10.3389/fmicb.2017.01501
17. Guisbiers G, Mejía-Rosales S, Deepak FL. 2012. Nanomaterial properties: size and shape dependencies. *J Nanomater* 2012: 20. https://doi.org/10.1155/2012/180976
18. Wu Q, Miao W, Zhang Y, Gao H, Hui D. 2020. Mechanical properties of nanomaterials: a review. *Nanotechnol Rev* 9(1): 259-273. https://doi.org/10.1515/ntrev-2020-0021
19. Shrivastava S, Dash D. 2009. Applying nanotechnology to human health: revolution in biomedical sciences. *J Nanotechnol* 2009: 1-15. https://doi.org/10.1155/2009/184702
20. Khan I, Saeed K, Khan I. 2019. Nanoparticles: properties, applications, and toxicities. *Arab J Chem* 12(7): 908-931. https://doi.org/10.1016/j.arabjc.2017.05.011
21. Ravichandran R. 2010. Nanotechnology applications in food and food processing: innovative green approaches, opportunities, and uncertainties for global market. *Int J Green Nanotechnol Phys Chem* 1(2): 72-96. https://doi.org/10.1080/19430871003684440
22. Han JH. 2014. Edible Films and Coatings: A Review. In Han JH (ed) Innova Food Packaging. Academic Press, pp 213-255.
23. Galus S, Kibar EAA, Gniewosz M, Kraśniewska K. 2020. Novel materials in the preparation of edible films and coatings – a review. *Coatings* 10(7): 674. https://doi.org/10.3390/coating10070674
24. Ulusoy BH, Yildirim FK, Hecer C. 2018. Edible films and coatings: a good idea from past to future technology. *J Food Technol Res* 5(1): 28-33. https://doi.org/10.18488/journal.58.2018.51.28.33
25. García MA, Martino MN, Zaritzky NE. 1999. Edible starch films and coatings characterization: scanning electron microscopy, water vapour, and gas permeabilities. *Scanning* 21(5): 348-353. https://doi.org/10.1002/sca.4950210508
26. Socaciu MI, Fogarasi, M, Semeniuc CA, Socaci SA, Rotar MA, et al. 2020. Formulation and characterization of antimicrobial edible films based on whey protein isolate and tarragon essential oil. *Polymers* 12(8): 1748. https://doi.org/10.3390/polym12081748
27. Aloui H, Khwaldia K. 2016. Natural, antimicrobial edible coatings for microbial safety and food quality enhancement. *Compr Rev Food Sci Food Saf* 15: 1080-1103. https://doi.org/10.1111/1541-4337.12226
28. Guimarães A, Abrunhosa L, Pastrana LM, Cerqueira MA. 2018. Edible films and coatings as carriers of living micro-organisms: a new strategy towards bio preservation and healthier foods. *Compr Rev Food Sci Food Saf* 17: 594-614. https://doi.org/10.1111/1541-4337.12345
29. Erkmen O, Barazi AO. 2018. General characteristics of edible films. *J Food Biotechnol Res* 2(13): 1-4.
30. Dhaka RK, Upadhyay A. 2018. Edible films and coatings: a brief overview. *Pharm Innov J* 7(7): 331-333.
31. Cotter PD, Hill C, Ross RP. 2005. Bacteriocins: developing innate immunity for food. *Nat Rev Microbiol* 3(10): 777-788. https://doi.org/10.1038/nrmicro1273
32. Yang SC, Lin CH, Sung CT, Fang JY. 2014. Antibacterial activities of bacteriocins: application in foods and pharmaceuticals. *Front Microbiol* 5: 241. https://doi.org/10.3389/fmicb.2014.00241
33. Soltani S, Hammami R, Cotter PD, Rebuffat S, Said LB, et al. 2021. Bacteriocins as a new generation of antimicrobials: toxicity aspects and regulations. *FEMS Microbiol Rev* 45(1): 1-24. https://doi.org/10.1093/femsre/fuaa039
34. Gautam N, Sharma N. 2009. Bacteriocin: safest approach to preserve food products. *Indian J Microbiol* 49(3): 204-211. https://doi.org/10.1007/s12088-009-0048-3
35. Silva CCG, Silva SPM, Ribeiro SC. 2018. Application of bacteriocins and protective cultures in dairy food preservation. *Front Microbiol* 9: 594. https://doi.org/10.3389/fmicb.2018.00594
36. Sharma K, Kaur S, Singh R, Kumar N. 2021. Classification and mechanism of bacteriocin induced cell death: a review. *J Microbiol Biotechnol Food Sci* 11(3): e3733. https://doi.org/10.15414/jmbfs.3733
37. Parada JL, Caron CR, Medeiros ABP, Soccol CR. 2007. Bacteriocins from lactic acid bacteria: purification, properties and use as bio preservatives. *Braz Arch Biol Technol* 50: 512-542. https://doi.org/10.1590/S1516-89132007000300018

38. Thapar P, Salooja MK. 2022. Bacteriocins: Applications in Food Preservation and Therapeutics. In Laranjo M (ed) *Lactobacillus* - A Multifunctional Genus. IntechOpen.
39. Bharti V, Mehta A, Singh S, Jain N, Ahirwal L, et al. 2015. Bacteriocin: a novel approach for preservation of food. *Int J Pharm Pharm Sci* 7(9): 20-29.
40. Rebuffat S. 2011. Bacteriocins from Gram-negative Bacteria: A Classification? In Drider D, Rebuffat S (eds) Prokaryotic Antimicrobial Peptides. Springer, New York.
41. Chen H, Hoover DG. 2003. Bacteriocin and their food applications. *Compr Rev Food Sci Food Saf* 2(3): 82-100. https://doi.org/10.1111/j.1541-4337.2003.tb00016.x
42. Settanni L, Corsetti A. 2008. Application of bacteriocins in vegetable food biopreservation. *Int J Food Microbiol* 121(2): 123-138. https://doi.org/10.1016/j.ijfoodmicro.2007.09.001
43. Negash AW, Tsehai BA. 2020. Current applications of bacteriocin. Int *J Microbiol* 2020: 1-7.
44. Rodríguez JM, Martínez MI, Kok J. 2002. Pediocin PA-1, a wide-spectrum bacteriocin from lactic acid bacteria. *Crit Rev Food Sci Nutr* 42(2): 91-121. https://doi.org/10.1080/10408690290825475
45. Mehta R, Arya R, Goyal K, Singh M, Sharma A. 2013. Bio-preservative and therapeutic potential of pediocin: recent trends and future perspectives. *Recent Patents Biotechnol* 7(3): 172-178.
46. Sidhu PK, Nehra K. 2021. Bacteriocins of Lactic Acid Bacteria as Potent Antimicrobial Peptides Against Food Pathogens. In Habib MK, Martín-Gómez C (eds) Biomimetics. IntechOpen.
47. Sulthana R, Archer AC. 2021. Bacteriocin nanoconjugates: boon to medical and food industry. *J Appl Microbiol* 131(3): 1056-1071. https://doi.org/10.1111/jam.14982
48. Zawrah MF, El-Moez SA, Center D. 2011. Antimicrobial activities of gold nanoparticles against major foodborne pathogens. *Life Sci J* 8(4): 37-44.
49. Bagde P, Vigneshwaran N. 2019. Improving the stability of bacteriocin extracted from *Enterococcus faecium* by immobilization onto cellulose nanocrystals. *Carbohydr Polym* 209: 172-180. https://doi.org/10.1016/j.carbpol.2019.01.027
50. Sidhu PK, Nehra K. 2019. Bacteriocin-nanoconjugates as emerging compounds for enhancing antimicrobial activity of bacteriocins. *J King Saud Univ Sci* 31(4): 758-767. https://doi.org/10.1016/j.jksus.2017.12.007
51. García-Toledo JA, Torrestiana-Sánchez B, Martínez-Sánchez CE, Tejero-Andrade JM, García-Bórquez A, et al. 2019. Nanoencapsulation of a bacteriocin from *Pediococcus acidilactici* ITV26 by micro fluidization. *Food Bioprocess Technol* 12(1): 88-97. https://doi.org/10.1007/s11947-018-2184-4
52. Mapelli C, Musatti A, Barbiroli A, Saini S, Bras J, et al. 2019. Cellulose nanofiber (CNF)–sakacin-a active material: production, characterization and application in storage trials of smoked salmon. *J Sci Food Agric* 99(10): 4731-4738. https://doi.org/10.1002/jsfa.9715
53. Chopra L, Singh G, Kumar JK, Sahoo DK. 2015. Sonorensin: a new bacteriocin with potential of an anti-biofilm agent and a food bio preservative. *Sci Rep* 5(1): 1-3. https://doi.org/10.1038/srep13412
54. Bahrami A, Delshadi R, Jafari SM, Williams L. 2019. Nanoencapsulated nisin: an engineered natural antimicrobial system for the food industry. *Trends Food Sci Technol* 94: 20-31. https://doi.org/10.1016/j.tifs.2019.10.002
55. Imran M, Revol-Junelles AM, René N, Jamshidian M, Akhtar MJ, et al. 2012. Microstructure and physico-chemical evaluation of nano-emulsion-based antimicrobial peptides embedded in bioactive packaging films. *Food Hydrocolloids* 29(2): 407-419. https://doi.org/10.1016/j.foodhyd.2012.04.010
56. Yang Y, Liu H, Wu M, Ma J, Lu P. 2020. Bio-based antimicrobial packaging from sugarcane bagasse nanocellulose/nisin hybrid films. *Int J Biol Macromol* 161: 627-635. https://doi.org/10.1016/j.ijbiomac.2020.06.081
57. Gomashe AV, Dharmik PG. 2012. Synergistic effect of gold nanoparticles and bacteriocin against food blemishing microbes: a novel approach for food packaging material preparation. *Glob J Res Anal* 3: 1-3.
58. Krivorotova T, Cirkovas A, Maciulyte S, Staneviciene R, Budriene S, et al. 2016. Nisin-loaded pectin nanoparticles for food preservation. *Food Hydrocolloids* 54: 49-56. https://doi.org/10.1016/J.FOODHYD.2015.09.015
59. Bi L, Yang L, Bhunia AK, Yao Y. 2011. Carbohydrate nanoparticle-mediated colloidal assembly for prolonged efficacy of bacteriocin against food pathogen. *Biotechnol Bioeng* 108(7): 1529-1536. https://doi.org/10.1002/bit.23099
60. Wu H, Teng C, Liu B, Tian H, Wang J. 2018. Characterization and long-term antimicrobial activity of the nisin anchored cellulose films. *Int J Biol Macromol* 113: 487-493. https://doi.org/10.1016/j.ijbiomac.2018.01.194
61. Pinilla CM, Brandelli A. 2016. Antimicrobial activity of nanoliposomes co-encapsulating nisin and garlic extract against Gram-positive and Gram-negative bacteria in milk. *Innov Food Sci Emerg Technol* 36: 287-293. https://doi.org/10.1016/j.ifset.2016.07.017
62. Mirhosseini M, Afzali M. 2016. Investigation into the antibacterial behavior of suspensions of magnesium oxide nanoparticles in combination with nisin and heat against *Escherichia coli* and *Staphylococcus aureus* in milk. *Food Control* 68: 208-215. https://doi.org/10.1016/j.foodcont.2016.03.048
63. Jin T, Gurtler JB. 2011. Inactivation of *Salmonella* in liquid egg albumen by antimicrobial bottle coatings infused with allyl isothiocyanate, nisin and zinc oxide nanoparticles. *J Appl Microbiol* 110(3): 704-712. https://doi.org/10.1111/j.1365-2672.2011.04938.x
64. Mirhosseini M, Marvasti SH. 2017. Antibacterial activities of copper oxide (CuO) nanoparticles in combination with nisin and ultrasound against foodborne pathogens. *Iran J Med Microbiol* 11(5): 125-135.
65. Lopes NA, Brandelli A. 2018. Nanostructures for delivery of natural antimicrobials in food. *Crit Rev Food Sci Nutr* 8(13): 2202-2212. https://doi.org/10.1080/10408398.2017.1308915
66. Boelter JF, Brandelli A. 2016. Innovative bio nanocomposite films of edible proteins containing liposome-encapsulated nisin and halloysite nano clay. *Colloids Surf* 145: 740-747. https://doi.org/10.1016/j.colsurfb.2016.05.080
67. Zou Y, Lee HY, Seo YC, Ahn J. 2012. Enhanced antimicrobial activity of nisin-loaded liposomal nanoparticles against foodborne pathogens. *J Food Sci* 77(3): 165-170.
68. Gedarawatte ST, Ravensdale JT, Al-Salami H, Dykes GA, Coorey R. 2021. Antimicrobial efficacy of nisin-loaded bacterial cellulose nanocrystals against selected meat spoilage lactic acid bacteria. *Carbohydr Polym* 251: 117096. https://doi.org/10.1016/j.carbpol.2020.117096
69. Kazemeini H, Azizian A, Shahavi MH. 2019. Effect of chitosan nano-gel/emulsion containing bunium persicum essential oil and nisin as an edible biodegradable coating on *Escherichia coli* O157:H7 in rainbow trout fillet. *J Water Environ Nanotechnol* 4(4): 343-349. https://doi.org/10.22090/jwent.2019.04.008
70. Kumar A, Behl T, Chadha S. 2020. Synthesis of physically crosslinked PVA/Chitosan loaded silver nanoparticles hydrogels with tunable mechanical properties and antibacterial effects. *Int J Biological Macromol* 149: 1262-1274. https://doi.org/10.1016/j.ijbiomac.2020.02.048
71. Boro RC, Kaushal J, Nangia Y, Wangoo N, Bhasin A, et al. 2011. Gold nanoparticles catalyzed chemiluminescence immunoassay for detection of herbicide 2,4-dichlorophenoxyacetic acid. *Analyst* 136(10): 2125-2130. https://doi.org/10.1039/c0an00810a
72. Pandit R. 2021. Biocompatible Polymers Impregnated with Nisin and Nanoparticles for Food preservation. In Rai M, Alves dos Santos C (eds) Biopolymer-Based Nano Films. Elsevier, pp 85-98.
73. Fahim HA, Khairalla AS, El-Gendy AO. 2016. Nanotechnology: a valuable strategy to improve bacteriocin formulations. *Front Microbiol* 7: 1385. https://doi.org/10.3389/fmicb.2016.01385

74. Troncoso OP, Torres FG. 2020. Bacterial cellulose—graphene-based nanocomposites. *Int J Mol Sci* 21(18): 6532. https://doi.org/10.3390/ijms21186532

75. Andriani D, Apriyana AY, Karina M. 2020. The optimization of bacterial cellulose production and its applications: a review. *Cellulose* 27(12): 6747-6766. https://doi.org/10.1007/s10570-020-03273-9

76. Shi Z, Zhang Y, Phillips GO, Yang G. 2014. Utilization of bacterial cellulose in food. *Food Hydrocolloids* 35: 539-545. https://doi.org/10.1016/j.foodhyd.2013.07.012

77. Niyazbekova ZT, Nagmetova GZ, Kurmanbayev AA. 2018. An overview of bacterial cellulose applications. *Eur J Appl Biotechnol* 28(2).

78. Choi SM, Shin EJ. 2020. The nanofication and functionalization of bacterial cellulose and its applications. *Nanomaterials* 10(3): 406. https://doi.org/10.3390/nano10030406

79. Stanislawska A. 2016. Bacterial nanocellulose as a microbiological derived nanomaterial. *Adv Mater Sci* 16(4): 45. https://doi.org/10.1515/adms-2016-0022

80. Vilela C, Moreirinha C, Domingues EM, Figueiredo FM, Almeida A, et al. 2019. Antimicrobial and conductive nanocellulose-based films for active and intelligent food packaging. *Nanomaterials* 9(7): 980. https://doi.org/10.3390/nano9070980

81. George J, Ramana KV, Bawa AS. 2011. Bacterial cellulose nanocrystals exhibiting high thermal stability and their polymer nanocomposites. *Int J Biol Macromol* 48(1): 50-57. https://doi.org/10.1016/j.ijbiomac.2010.09.013

82. Azeredo HM, Barud H, Farinas CS, Vasconcellos VM, Claro AM. 2019. Bacterial cellulose as a raw material for food and food packaging applications. *Front Sustain Food Syst* 3: 1-7. https://doi.org/10.3389/fsufs.2019.00007

83. de Amorim JD, de Souza KC, Duarte CR, da Silva DI, de Assis SRF, et al. 2020. Plant and bacterial nanocellulose: production, properties and applications in medicine, food, cosmetics, electronics and engineering. a review. *Environ Chem Lett* 18(3): 851-869. https://doi.org/10.1007/s10311-020-00989-9

84. Qasim U, Osman AI, Al-Muhtaseb AA, Farrell C, Al-Abri M, et al. 2021. Renewable cellulosic nanocomposites for food packaging to avoid fossil fuel plastic pollution: a review. *Environ Chem Lett* 19(1): 613-641. https://doi.org/10.1007/s10311-020-01090-x

85. Kolesovs S, Semjonovs P. 2020. Production of bacterial cellulose from whey—current state and prospects. *Appl Microbiol Biotechnol* 104(18): 7723-7730. https://doi.org/10.1007/s00253-020-10803-9

86. Mudgil M, Gupta N, Nagpal M, Pawar P. 2012. Nanotechnology: a new approach for ocular drug delivery system. *Int J Pharm Pharm Sci* 4(2): 105-112.

86. Sá NM, Mattos AL, Silva LM, Brito ES, Rosa MF, et al. 2020. From cashew byproducts to biodegradable active materials: bacterial cellulose-lignin-cellulose nanocrystal nanocomposite films. *Int J Biol Macromol* 161: 1337-1345. https://doi.org/10.1016/j.ijbiomac.2020.07.269

87. Cazón P, Vazquez M, Velazquez G. 2019. Environmentally friendly films combining bacterial cellulose, chitosan, and polyvinyl alcohol: effect of water activity on barrier, mechanical, and optical properties. *Biomacromolecules* 21(2): 753-760. https://doi.org/10.1021/acs.biomac.9b01457

88. Nascimento ES, Barros MO, Cerqueira MA, Lima HL, de Fatima BM, et al. 2021. All-cellulose nanocomposite films based on bacterial cellulose nanofibrils and nanocrystals. *Food Packag Shelf Life* 29: 100715. https://doi.org/10.1016/j.fpsl.2021.100715

89. Li Q, Gao R, Wang L, Xu M, Yuan Y, et al. 2020. Nanocomposites of bacterial cellulose nanofibrils and zein nanoparticles for food packaging. *ACS Appl Nano Mater* 3(3): 2899-2910. https://doi.org/10.1021/acsanm.0c00159

90. George J, Kumar R, Kumar SVA, Ramana KV, Rajamanickam R, et al. 2014. Hybrid HPMC nanocomposites containing bacterial cellulose nanocrystals and silver nanoparticles. *Carbohydr Polym* 105: 285-292. https://doi.org/10.1016/j.carbpol.2014.01.057

91. Ludwicka K, Kaczmarek M, Białkowska A. 2020. Bacterial nanocellulose—a biobased polymer for active and intelligent food packaging applications: recent advances and developments. *Polymers* 12(10): 2209. https://doi.org/10.3390/polym12102209

92. Zhu H, Jia S, Yang H, Tang W, Jia Y, et al. 2010. Characterization of bacteriostatic sausage casing: a composite of bacterial cellulose embedded with ε-polylysine. *Food Sci Biotechnol* 19(6): 1479-1484. https://doi.org/10.1007/s10068-010-0211-y

93. Padrao J, Gonçalves S, Silva JP, Sencadas V, Lanceros-Méndez S, et al. 2016. Bacterial cellulose-lactoferrin as an antimicrobial edible packaging. *Food Hydrocolloids* 58: 126-140. https://doi.org/10.1016/j.foodhyd.2016.02.019

94. Zahan KA, Azizul NM, Mustapha M, Tong WY, Rahman MS. 2020. Application of bacterial cellulose film as a biodegradable and antimicrobial packaging material. *Mater Today Proc* 31: 83-88. https://doi.org/10.1016/j.matpr.2020.01.201

95. Salari M, Khiabani MS, Mokarram RR, Ghanbarzadeh B, Kafil HS. 2018. Development and evaluation of chitosan based active nanocomposite films containing bacterial cellulose nanocrystals and silver nanoparticles. *Food Hydrocolloids* 84: 414-423. https://doi.org/10.1016/j.foodhyd.2018.05.037

96. Criado P, Hossain FM, Salmieri S, Lacroix M. 2018. Nanocellulose in Food Packaging. In Cirillo G, Kozlowski MA (eds) Composites Materials for Food Packaging John Wiley and Sons, pp 297-329.

97. Adepu S, Khandelwal M. 2018. Broad-spectrum antimicrobial activity of bacterial cellulose silver nanocomposites with sustained release. *J Mater Sci* 53(3): 1596-1609. https://doi.org/10.1007/s10853-017-1638-9

98. Moghanjougi ZM, Bari MR, Khaledabad MA, Almasi H, Amiri S. 2020. Bio-preservation of white brined cheese (Feta) by using probiotic bacteria immobilized in bacterial cellulose: optimization by response surface method and characterization. *LWT* 117: 108603. https://doi.org/10.1016/j.lwt.2019.108603

99. Yordshahi AS, Moradi M, Tajik H, Molaei R. 2020. Design and preparation of antimicrobial meat wrapping nanopaper with bacterial cellulose and postbiotics of lactic acid bacteria. *Int J Food Microbiol* 321: 108561. https://doi.org/10.1016/j.ijfoodmicro.2020.108561

100. Fahim HA, Rouby W, El MA, El-Gendy AO, Khairalla AS, et al. 2017. Enhancement of the productivity of the potent bacteriocin avicin A and improvement of its stability using nanotechnology approaches. *Sci Rep* 7(1): 1-3. https://doi.org/10.1038/s41598-017-10157-9

101. Amer SA, Abushady HM, Refay RM, Mailam MA. 2021. Enhancement of the antibacterial potential of plantaricin by incorporation into silver nanoparticles. *J Genet Eng Biotechnol* 19(1): 1-6. https://doi.org/10.1186/s43141-020-00093-z

102. Kuswandi B, Asih NP, Pratoko DK, Kristiningrum N, Moradi M. 2020. Edible pH sensor based on immobilized red cabbage anthocyanins into bacterial cellulose membrane for intelligent food packaging. *Packag Technol Sci* 33(8): 321-332. https://doi.org/10.1002/pts.2507

103. Kuswandi B, Oktaviana R, Abdullah A, Heng LY. 2014. A novel on-package sticker sensor based on methyl red for real-time monitoring of broiler chicken cut freshness. *Packag Technol Sci* 27(1): 69-81. https://doi.org/10.1002/pts.2016

104. Sukhtezari S, Almasi H, Pirsa S, Zandi M, Pirouzifard M. 2017. Development of bacterial cellulose based slow-release active films by incorporation of *Scrophularia striata* Boiss. extract. *Carbohydr Polym* 156: 340-350. https://doi.org/10.1016/j.carbpol.2016.09.058

105. Quirós-Sauceda AE, Ayala-Zavala JF, Olivas GI, González-Aguilar GA. 2014. Edible coatings as encapsulating matrices for bioactive compounds: a review. *J Food Sci Technol* 51(9): 1674-1685. https://doi.org/10.1007/s13197-013-1246-x

106. Quintanilla-Carvajal MX, Camacho-Díaz BH, Meraz-Torres LS, Chanona-Pérez JJ, Alamilla-Beltrán L, et al. 2010. Nanoencapsulation: a new trend in food engineering processing. *Food Eng Rev* 2(1): 39-50. https://doi.org/10.1007/s12393-009-9012-6

107. Huang Y, Mei L, Chen X, Wang Q. 2018. Recent developments in food packaging based on nanomaterials. *Nanomaterials* 8(10): 830. https://doi.org/10.3390/nano8100830

108. Janjarasskul T, Krochta JM. 2010. Edible packaging materials. *Annu Rev Food Sci Technol* 1(1): 415-418.

109. Zambrano-Zaragoza ML, González-Reza R, Mendoza-Muñoz N, Miranda-Linares V, Bernal-Couoh TF, et al. 2018. Nanosystems in edible coatings: a novel strategy for food preservation. *Int J Mol Sci* 19(3): 705. https://doi.org/10.3390/ijms19030705

110. Zhu J, Huang Q. 2019. Nanoencapsulation of functional food ingredients. *Adv Food Nutr Res* 88: 129-165. https://doi.org/10.1016/bs.afnr.2019.03.005

111. Aswathanarayan JB, Vittal RR. 2019. Nanoemulsions and their potential applications in food industry. *Front Sustain Food Syst* 3: 95. https://doi.org/10.3389/fsufs.2019.00095

112. Maté J, Periago PM, Palop A. 2016. Combined effect of a nanoemulsion of D-limonene and nisin on *Listeria monocytogenes* growth and viability in culture media and foods. *Food Sci Technol Int* 22(2): 146-152.

113. Arora A, Padua GW. 2010. Nanocomposites in food packaging. *J Food Sci* 75(1): 43-49. https://doi.org/10.1111/j.1750-3841.2009.01456.x

114. Kumar V, Guleria P, Mehta SK. 2017. Nanosensors for food quality and safety assessment. *Environ Chem Lett* 15(2): 165-177. https://doi.org/10.1007/s10311-017-0616-4

115. Honarvar Z, Hadian Z, Mashayekh M. 2016. Nanocomposites in food packaging applications and their risk assessment for health. *Electron Phys* 8(6): 2531. https://doi.org/10.19082/2531

116. Chaudhry Q, Scotter M, Blackburn J, Ross B, Boxall A, et al. 2008. Applications and implications of nanotechnologies for the food sector. *Food Addit Contam* 25(3): 241-258. https://doi.org/10.1080/02652030701744538

117. Pradhan N, Singh S, Ojha N, Shrivastava A, Barla A, et al. 2015. Facets of nanotechnology as seen in food processing, packaging, and preservation industry. *BioMed Res Int* 2015. https://doi.org/10.1155/2015/365672

118. Bhattacharya T, Soares GA, Chopra H, Rahman MM, Hasan Z, et al. 2022. Applications of phyto-nanotechnology for the treatment of neurodegenerative disorders. *Materials* 15(3): 804. https://doi.org/10.3390/ma15030804

118. Fuertes G, Soto I, Carrasco R, Vargas M, Sabattin J, et al. 2016. Intelligent packaging systems: sensors and nanosensors to monitor food quality and safety. *J Sensors* 2016. https://doi.org/10.1155/2016/4046061

119. Ameta SK, Rai AK, Hiran D, Ameta R, Ameta SC. 2020. Use of Nanomaterials in Food Science. In Ghorbanpour M, Bhargava P, Varma A., Choudhary D (eds) Biogenic Nano-particles and their Use in Agro-ecosystems. Springer, Singapore, pp 457-488.

120. Thiruvengadam M, Rajakumar G, Chung IM. 2018. Nanotechnology: current uses and future applications in the food industry. *3 Biotech* 8(1): 1-3. https://doi.org/10.1007/s13205-018-1104-7

121. Burgos N, Mellinas AC, García-Serna E, Jiménez A. 2017. Nanoencapsulation of Flavor and Aromas in Food Packaging. In Grumezescu AM (ed) Food Packagning, Academic Press, pp 567-601.

122. Das S, Chaudhari AK, Dwivedy AK, Upadhyay N, Singh VK, et al. 2020. Nanoencapsulation Technology: Boon to Food Packaging Industries. Bhushan I, Singh V, Tripathi D (eds) Nanomaterials and Environmental Biotechnology. Springer, pp 17-40.

123. Majid I, Thakur M, Nanda V. 2018. Innovative and Safe Packaging Technologies for Food and Beverages: Updated Review. In Panda S, Shetty P (eds) Innovations in Technologies for Fermented Food and Beverage Industries. Springer Cham. pp 257-287.

124. Jafarzadeh S, Nafchi AM, Salehabadi A, Oladzad-Abbasabadi N, Jafari SM. 2021. Application of bio-nanocomposite films and edible coatings for extending the shelf life of fresh fruits and vegetables. *Adv Colloid Interface Sci* 291: 102405. https://doi.org/10.1016/j.cis.2021.102405