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Review Article

Bacterial nanocellulose in cheese technology: Applications, advantages, and future directions

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Abstract

Bacterial nanocellulose (BNC) is a natural exopolysaccharide produced by certain kinds of bacterial strains, such as those of the genus *Komagataeibacter*. BNC is an eco-friendly natural biopolymer with unique characteristics. BNC and its derivatives (nanofibrils and nanocrystals) have been reported to have high water adsorption properties, good thermal stability, and excellent mechanical properties. It was recently shown that BNC has a potential to be used in food. However, there is very little research on the use of BNC in dairy products such as cheese. In this article, we examine the potential future applications of BNC in cheese industry, as a provider of specific functionalities and as a packaging material. As an additive, BNC can be used as an emulsion stabilizer, gelling agent, thickener, encapsulating agent, fat replacer, or dietary fiber source. BNC can also be used to formulate films or coatings aimed at protecting and improving the shelf life of cheeses.

Keywords: Biocellulose, Cellulose production, Cheese shelf life, Composite material, Encapsulation.

Introduction

Cellulose is the most abundant organic polymer, primarily found in plants (Zhang et al., 2021). Chemically, it consists of linear chains comprised of numerous glucose units linked together by β-(1→4) glycosidic linkages. The linear chains in cellulose are capable of coming close together and forming strong intermolecular hydrogen bonds with their neighbors. Moreover, certain bacteria from *Komagataeibacter, Enterobacter, Escherichia, Klebsiella, Lactobacillus Burkholderia, Erwinia, Agrobacterium*, *Rhizobium,* and *Sarcina* genera synthesize, as a bottom-up approach, a nano-structured cellulose known as bacterial nanocellulose (BNC), bacterial cellulose (BC), biocellulose or microbial cellulose, with different production yields (Dourado et al., 2016; Martins et al., 2023). *Komagataeibacter* spp., formerly known as *Gluconacetobacter* or *Acetobacter*, is the most well studied acetic acid BNC-producer bacteria both for basic and applied production (Acharyya et al., 2024). *K. xylinus* ATCC 53582 is the BNC producer with the highest known yield (i.e., 6-7 g/L in Hestrin–Schramm - HS - medium and even higher yields from agricultural by-products) (Ludwicka et al., 2020). HS, which contains glucose, yeast extract, peptone, Na_2HPO_4, and citric acid (pH 5 - 5.5), is the most commonly used culture medium for producing BNC in laboratories in the static and agitated conditions (Costa et al., 2017).

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BNC nanofibrils build a highly porous, ultra-thin three-dimensional structure with a large surface area and aspect ratio, and provide specific properties such as a high water-retention (more than 200 times its dry weight) with proper plasticity. The presence of many hydroxyl groups on the surface of BNC facilitates the adsorption of many types of functional substances (Razavi et al., 2020). Then, BNC reveals special characteristics over plant-based cellulose such as high purity, water, and oil- binding capacities, crystallinity (80-90%), mechanical properties (elastic modulus of 15-138 GPa, tensile strength of 20-2000 MPs), thermal stability (up to 300 °C), high moldability *in situ,* and more than 90% transparency (Ahankari et al., 2021; Marchetti & Andrés, 2021). All the mentioned specifications make BNC a suitable nanomaterial for food application (Wang et al., 2024). Then, the potential of BNC for food applications has been demonstrated over the years (Wang et al., 2025). Although BNC presents great utilization potential for the cheese industry (**Figure 1**), limited studies have been carried out in this area (Shafiei et al., 2024; Vázquez et al., 2024; Xia et al., 2023). The focus of the current review is on the potential future use of all types of BNC (wet and dried BNC, nanofibrils, and nanocrystals) as packaging material, absorbing pad or as additive in cheese production.

BNC as packaging material and absorbing pad

Cheese can become contaminated with a variety of microorganisms during transportation and storage such as coliforms, yeasts, heterofermentative lactic acid bacteria, and spore-forming bacteria can spoil the product (Cui et al., 2020). Petroleum derived polymers are currently the most common type of food packaging due to their relatively low cost, suitable barrier and mechanical properties, heat and solvents resistance (Moradi, Kousheh et al., 2021). However, these petroleum products are not biodegradable and pose a challenge to the environment (Tajeddin & Arabkhedri, 2020). BNC can act as a supportive base for different types of functional substances (e.g., antimicrobials, antioxidants, nutraceuticals, dyes, ripening agents, etc.) or as a nanofiller material for development of sustainable composite packaging material (Acharyya et al., 2024).

BNC as a base polymer in active cheese packaging

BNC film has high porosity, good mechanical properties, and malleability, and can serve as a polymeric base for the fabrication of active and intelligent dairy packaging (Azeredo et al., 2019; Yu et al., 2024). In active packaging, special agents including antimicrobial, antifungal, and antioxidant are incorporated into the BNC film in order to provide the desired active properties (Ludwicka et al., 2020). Two main methods can be used for this purpose, the *ex-situ* and the *in-situ* method (Kraśniewska et al., 2020; Lotfi Javid et al., 2024), according to whether the active agent is added to BNC after or during the fermentation. For poorly water-soluble substances, techniques such as encapsulation and nano and microencapsulation can be used (Gupta et al., 2019; Marquele-Oliveira et al., 2019). Shafiei et al. (2024) developed antimicrobial sachets by encapsulating *Zataria multiflora* essential oil (ZMEO) within halloysite nanotubes (HNTs) and incorporating them into BNC films for cheese packaging. The BNC sachets with HNTs:ZMEO at a 2:1 ratio (20%) showed effective reduction of *E. coli* O157:H7 and sustained essential oil release without toxicity. This innovative packaging offers a promising approach to extend cheese shelf life safely. Moreover, due to the presence of various reactive groups within the BNC 3D structure, surface modification can be a practical alternative approach (Badshah et al., 2018). In an alternative way, BNC can be soaked in another polymer (e.g., chitosan, alginate, gums, etc.) containing the target active material. More recently, an antimicrobial, antioxidant and antibiofilm BNC membranes were developed by coating BNC film with a chitosan solution (Cabañas-Romero et al., 2020). The prepared film exhibited antimicrobial activity on different types of microorganisms such as *Candida albicans, Staphylococcus aureus*, and *Pseudomonas aeruginosa* and inhibited biofilm formation of mentioned microorganisms.

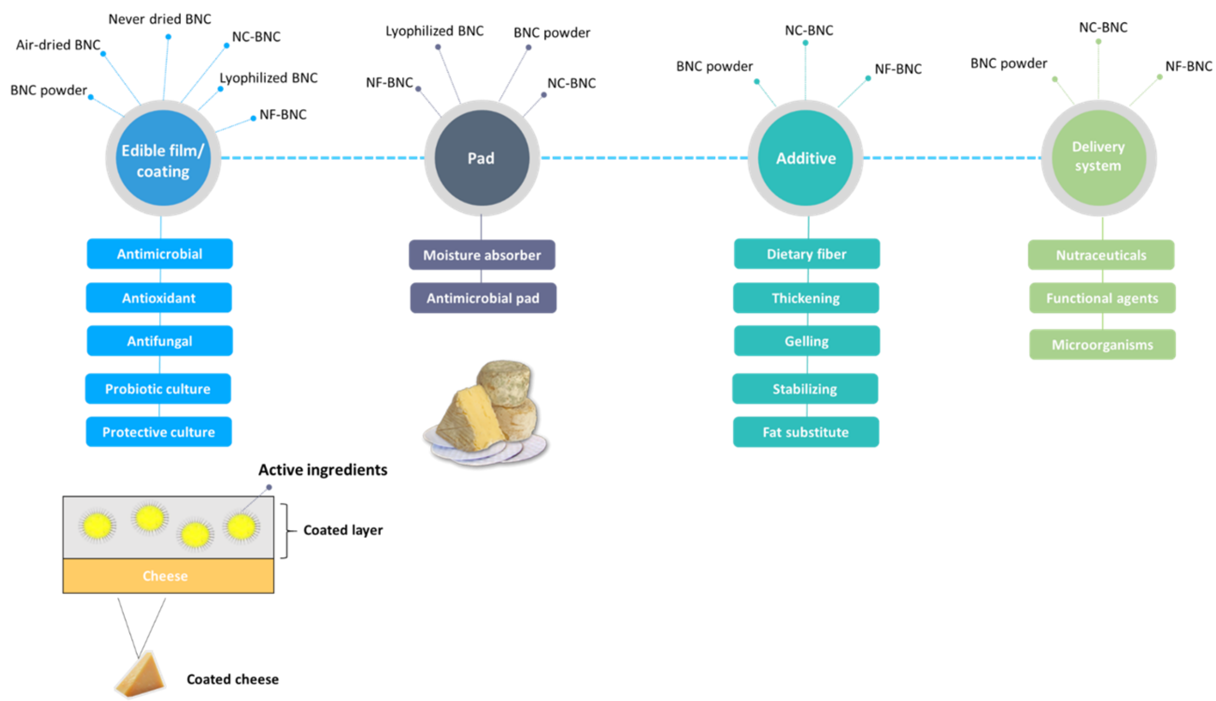

Figure 1. Potential applications of different types of bacterial nanocellulose (BNC) in cheese production and packaging. NF-BNC and NC-BNC stand for nanofibrils and nanocrystals obtained from BNC, respectively. The picture of cheese was included by permission of Sirane Ltd.

In the one case, the prepared BNC film or coating solution is wrapped around the cheese, or in some varieties (e.g., white cheese) is placed on top of the cheese before sealing the container with aluminum foil. Bio-based BNC film containing different kinds of compounds such as antibacterial (Lotfi Javid et al., 2024; Nikfarjam et al., 2025) and beneficial microorganisms and their metabolites (Shafipour Yordshahi et al., 2020) have been developed. The selection of active ingredients in the BNC film may vary with respect to the type of cheese and the type of spoilage. Active agents such as herbal extract, essential oils, nisin, enzybiotics, organic acids, nanomaterials, antimicrobial peptides, and natamycin are the most important compounds recommended for loading into BNC films used for cheese packaging. Vázquez et al. (2024) developed laminated films combining BNC and chitosan, plasticized with glycerol and enriched with grape bagasse extract (GE) for antioxidant properties. The films exhibited tensile strength between 16.9 and 32.7 MPa, with elongation increasing up to fourfold compared to films without GE. Incorporation of GE and glycerol also improved puncture resistance. Applied as cheese separators, these films reduced lipid oxidation by 67.3% in Havarti cheese over 60 days, demonstrating their potential as sustainable, active packaging materials that enhance both mechanical performance and food preservation. Lima Silva et al. (2020) incorporated nisin (2500 IU/mL) into BNC by *ex-situ* method with 4 h exposure, and found that the membrane obtained was effective in reducing *Listeria monocytogenes* by 1 $\log_{10}$ CFU/g in Minas Frescal cheese during storage at 10 °C. In another work with potential application in cheese, antimicrobial BNC paper was developed by immersion in a nisin solution with concentrations of 250 or 500 µg/mL (dos Santos et al., 2018). The developed film presented antimicrobial activity against *E. coli*, while no activity was found on *P. aeruginosa*.

BNC could also be a suitable matrix to develop enzymatically active film using antibacterial enzymes (enzybiotics substances e.g., lysozyme, laccase, etc.) and lipolytic /proteolytic ripening enzymes for cheese application. It appears that BNC fibers can improve the enzyme immobilization and efficiency of enzyme in BNC (Yuan et al., 2018). Lysozyme can be used as a replacer for nitrate and nisin for cheese preservation. In one study, lysozyme was incorporated into NF-BNC film by physical adsorption for 18 h (Buruaga-Ramiro, et al., 2020a). The obtained film represented high stability and durability and lysozyme retained its activity in BNC during 80 days of storage. In a similar work, laccase, a multicopper oxidase, with antibacterial activity on both Gram-positive and Gram-negative bacteria was immobilized by *ex-situ* method in lyophilized BNC (Sampaio et al., 2016). Laccase is a crosslinking enzyme with the ability to crosslink caseins and lactoglobulins, therefore, exhibits a promising performance to increase cheese yield (Loi et al., 2020). In a study with potential application in cheese, authors immobilized lipase in BNC film via physical adsorption, and found no significant differences in morphological and structural aspects of BNC after loading lipase. Lipase in BNC showed higher thermal stability, durability, and retained 60% activity over time (Buruaga-Ramiro et al.,2020b). No consideration was given to the effect of BNC film with enzymes on cheese. The developed film may be used for cheese ripening.

However, some studies have highlighted the importance of BNC film for the immobilization of probiotics (Motalebi Moghanjougi et al., 2020) and postbiotics (Shafipour Yordshahi et al., 2020) for food application. In this case, the probiotic/postbiotics are immobilized in BNC film by *in-situ* or *ex-situ* techniques instead of the direct addition of microorganisms into the cheese formulation or surface. Motalebi Moghanjougi et al. (2020) investigated the potential of BNC film as support for *Lactobacillus acidophilus* and *Bifidobacterium animalis* in free and encapsulated forms. They found a significant antagonistic activity of prepared probiotic BNC film on microbial growth on Feta cheese. The preparation of a BNC film using probiotics may be an important aspect of BNC in manufacturing active and nutritious cheese packaging materials. Some authors have used *in-situ* technique to load probiotics into the BNC film, but it is interesting to mention that although probiotics are protected efficiently *in-situ* immobilization, but this approach is impractical since further routine washing of synthesized BNC with an alkaline solution at higher temperatures can inactive bacterial cells (Azeredo et al., 2019).

The incorporation of postbiotics of probiotic and protective cultures is a novel way to overcome the direct use of microorganisms (Moradi et al., 2020). In this approach, postbiotics, which are known as soluble metabolites released by a probiotic and protective cultures during the growth in broth culture (Moradi et al., 2021), are harvested from a fermentation medium and then, incorporate into BNC. Although some authors reported the potential of postbiotics-BNC film as a novel material for food packaging (Shafipour Yordshahi et al., 2020), no work has been done previously to deal with the application of postbiotics incorporated BNC film in dairy products.

NF-BNC and NC-BNC with or without preservatives or polymers can be also used for cheese coating during storage time in order to extend the shelf life (Figure 1). In this case, BNC solution can provide a transparent layer around cheese, and decrease the weight loss, microbial and chemical spoilage, and improve the structure and firmness of cheese cuts.

BNC as an absorbent/ antibacterial pad

The growth of fungi and bacteria in cheese depends on a number of desirable growth factors. Moisture is one of the most important factors that promote the growth of mold in cheese (Garnier et al., 2017). As a result of high surface area, BNC presents high water capacity retention, (over 100 times of its own weight) (Cazón & Vázquez, 2021), therefore, for cheese application, a BNC-based absorbent pad can also be a practical approach (Figure 1). In this system, BNC pad/foam is prepared in any size, shape with or without active compounds. BNC pad/foam is an ultra-light material with the capability to absorb excess moisture up to several times its weight (Ferreira et al., 2020). Moreover, by loading antibacterial and antifungal agents such as sodium benzoate, potassium sorbate, calcium lactate, calcium ascorbate, nisin, and natamycin, BNC pad can prevent mold/bacterial growth and help to ensure a high level of sterility for the cheese cut.

BNC as a nanofiller in cheese packaging material

In an alternative approach to films and coatings from raw BNC, BNC in the forms of NF-BNC and NC-BNC can be used in an optimum concentration as a superior filler/enhancer nanomaterial in fabrication of packaging material or as a film-forming solution with other commonly used polymers in cheese packaging (High-density polyethylene, polypropylene, and polystyrenes) (Silva et al., 2020), and bio-based polymers (Oliveira-Alcântara et al., 2020; Viana et al., 2018). In this case, NF-BNC and NC-BNC can interact with the main polymer(s) by hydrogen bonds and reinforce gas and water permeability, mechanical and thermal properties of prepared film/coating (Cazón & Vázquez, 2021). The fabricated film/coating material with or without preservative can provide a layer with the ability to extend the shelf life and quality of cheese. Moreover, BNC can control the release of active agents such as antimicrobial/antifungal additives from packaging material or coating solution into the products (Zhang et al., 2021). More recently, prebiotic/probiotic active film by cashew gum and NF-BNC was developed (Oliveira-Alcântara et al., 2020). NF-BNC was prepared via oxidation mediated by 2,2,6,6-tetramethyl-1-piperidinoxyl and cashew gum was used to adjust the high viscosity of NF-BNC. The probiotic *Bacillus coagulans* was stable for 45 days at 4 °C and ambient temperature. The addition of prebiotic fructooligosaccharides improved the viability of probiotic in the composite film. Although the researchers have not used the prepared film on food, this mixture or similar BNC-based probiotic/prebiotic complex in the form of film or film-forming solution would probably be suitable for use in cheese. Moreover, incorporating NC- and NF-BNC into protein and polysaccharides polymers can reduce the water vapor permeability of the prepared composite film/ solution (Wang et al., 2018).

BNC as a base polymer in intelligent food packaging

Intelligent packaging is a major innovation in the food packaging industry. Intelligent food materials are attached to the package as a label/tag and directly provide information of the freshness and any modification in storage temperature of food by a visible color change in a real-time way (Cheng et al., 2022). Currently, food freshness indicators and time-temperature indicators are widely used and widely available approaches for food packaging in the market (Zhan et al., 2025). Recently, attempts were made to fabricate BNC-based food packaging intelligent materials. It was clearly demonstrated that due to its porous, 3D structures and special adsorption/ holding capacity, BNC is an excellent polymer base for different pH (e.g., anthocyanins) and temperature (e.g., dyes, enzymes, and microbial cells) sensitive substances. Although freshness-sensing BNC film has been developed in order to monitor the freshness of meat (Lv et al., 2025), shrimp (Chen et al., 2024), fish (Cheng et al., 2025), and milk (Kuswandi et al., 2020), no work performed in the cheese. In a study, Li et al. (2024) developed versatile pH-sensitive films by stabilizing anthocyanin-loaded Pickering emulsions using enzymatically green-synthesized bacterial cellulose nanoparticles (BCNPs). The BCNPs enhanced emulsion stability, improved anthocyanin dispersion, and boosted the colorimetric sensitivity of the films across a broad pH range. These intelligent films showed excellent visual responsiveness, structural uniformity, and potential application in real-time monitoring of food freshness in active packaging systems.

BNC as a delivery agent

Micro- and nano-encapsulation are techniques used in the food industry to protect different types of materials (e.g., nutraceuticals, functional agents, and microorganisms) that may lose their function by degradation during processing or storage (Saifullah et al., 2019). BNC serves as an alternative green wall material to different biomaterials (e.g., alginate, chitosan, sodium caseinate, and starch) that are commonly used for encapsulation. In comparison to the commercial celluloses, BNC exhibits better emulsifying capability (Paximada, Tsouko, et al., 2016). This ability depend on factors such as BNC type and concentration, pH and ionic forces, method of preparation, and the presence of emulsifiers (Saffarionpour, 2020). In encapsulation, BNC, BNC nanocrystals, and nanofibers can be used to protect and carry various nutraceuticals and flavor compounds as well as microorganisms (e.g., probiotics) in the form of surfactant-free emulsions (i.e., Pickering emulsions) (Gedarawatte et al., 2021; Li et al., 2021; Saffarionpour, 2020; Yan et al., 2017; Zhai et al., 2018). In a study, researchers developed multifunctional gelatin-based films incorporating bacterial cellulose nanocrystals (BCNs) and CA-ε-polylysine Pickering emulsions via an ultrasonic self-assembly strategy (Xia et al., 2023). The resulting

GL-CA-εPL films exhibited strong antioxidant, antimicrobial, UV-shielding, and biodegradable properties. When applied to fresh mozzarella cheese, the films effectively delayed spoilage and lipid oxidation without altering sensory quality. These BCN-based Pickering films offer a sustainable and high-performance alternative for active food packaging. In comparison to CNF and CNC which have medium and short-length fibers, respectively; powdered BNC (prepared without any chemical and physical treatments) has longer fibers. This is an important specification of BNC in the production of emulsion or encapsulation systems (Lu et al., 2021). Moreover, due to appropriate hydration and dispersion, NF-BNC has a major priority to cellulose nanocrystals to be used in Pickering emulsions (Li et al., 2019). Physical size, the volume of oil, and solid content affected the emulsifying character of NF-BNC. In addition, the impact of pH, temperature, and ionic strength on emulsion`s stability was negligible. NF-BNC can decline the surface tension of oil/water droplets and improve system stability by only 0.05% at 20–100 °C for 4 weeks (Zhai et al., 2018). Jayani et al. (2020) produced NF-BNC and investigated its function as a carrier for a potential probiotic, i.e., *Lactobacillus acidophilus,* and reported a survival rate of 71% for probiotics during the storage at 35 °C. Nisin at different concentrations loaded on NC-BNC via complexation method (Gedarawatte et al., 2021). NC-BNC and NC-BNC- nisin complex showed -43 and ≥ 30 mV zeta potential, respectively. Based on the nisin concentration (2, 2.5, and 5 mg/mL), various encapsulation efficiency (80.5 to 93.3%) was reported, which indicates that the hydrophilic character and large fiber surface of NC-BNC may facilitate the load of nisin in BNC. There were no changes to the mechanical strength of the complex. The BNC with nisin at 2 and 2.5 mg/mL concentrations exhibited antibacterial activity on *Lactobacillus rhamnosus* LBM1 and *Leuconostoc mesenteroides* LBM2. Cheese is a good candidate for this type of application. Lower nisin encapsulation efficiency gains with up to 60% have been reported in previous works using alginate-chitosan nanoparticles (Zimet et al., 2018) and poly-γ-glutamic acid/chitosan nanoparticles (Cui et al., 2017). Colloidal particle consists of NF-BNC and soy protein isolate with an improved in properties was successfully developed as a stabilizer for high internal phase emulsion with 75% oil phase (Liu et al., 2021). In this system, both molecules interacted mainly by hydrogen bonds, and an improvement in emulsification of SPI was achieved. In another work, biological modification of NC-BNC with sodium alginate changed the morphology and the amphiphilicity of BNC. The prepared BNC-alginate complex revealed an ability to stabilize o/w Pickering emulsions (Jiang et al., 2020).

BNC as cheese additive

Dietary fiber

Today, the health role of dietary fiber in the human diet is obvious. Fibers are divided into soluble and insoluble fibers, which have been considered due to their special properties of the role of prebiotics, lowering cholesterol, increasing stool volume and improving gastrointestinal function and water absorption. BNC is indigestible and its nanofibers are a type of dietary fiber that is classified as safe (GRAS) since 1992 (Gedarawatte et al., 2021; Shi et al., 2014). The use of BNC as a dietary fiber claimed to present several advantages, such as purity, utilizing in different form and shape with a possibility to obtain from a safe and abundant source (Shi et al., 2014). The hypolipidemic and hypocholesterolemic effects of BNC are higher than plant cellulose (Chau et al., 2008), then it can be used in cheese as a source of dietary fiber.

Fat replacer

Due to the adverse effects of high-fat foods on human health, the research to find out novel and effective fat replacer has been expanded and carbohydrate-based fat substitutes have been studied due to their lower calorie content than fat. BNC has the potential to be used as an additive to reduce the calories of high-fat food and prevent fat-related health risks (Chen et al., 2020). Although studies have been carried out on the use of BNC as a fat replacer in ice cream, meatballs, and surimi (Azeredo et al., 2019; Guo et al., 2018), no prior work has been conducted in cheese. BNC alone or in combination with other texture modifiers can bind water and enhance the viscosity and gelling properties of certain types of cheese. BNC as a cost-effective thickener can be used in O/W emulsion, and also helps to produce a smooth, long, and extensible texture similar to processed cheese. For example, BNC in lower concentration than xanthan gum and locust bean gums represented similar viscosity in whey protein isolate (Paximada, Koutinas, et al., 2016).

Stabilizing, gelling, and thickening agents

Currently, there are many types of gum-based stabilizers such as gellan, carrageenan, xanthan, and locust bean gum, that are used alone or in combination to improve the quality of different food due to their excellent emulsification and stabilization properties. However, their applications are limited due to costs reasons, highly sophisticated extraction processes, and safety issues (Mu et al., 2019). BNC has been proposed as an alternative structural stabilizer and rheological modifier for cheese formulation, and mainly cream cheese to avoid syneresis and improve the viscosity of the aqueous phase (Brighenti et al., 2020). In comparison to commercial celluloses, changes in pH, temperature, and ionic force do not affect the BNC emulsion (Guo et al., 2018; Paximada, Tsouko, et al., 2016). In this case, BNC adsorbs to the oil-water interface and sets up a steric layer on oil droplets, and consequently, inhibits coalescence (Marchetti & Andrés, 2021). However, BNC fibers reveal good compatibility with protein and set a strong 3D- gel-like structure in the product, and keep food ingredients and water. In addition, the hydrophilic character of BNC assists more water retention (Marchetti & Andrés, 2021). There is limited work on the application of nanocellulose as a natural food stabilizer (Parés et al., 2018), and some cheese varieties (e.g., cream cheese) may suitable products for this application.

Conclusion

Both plant-based cellulose and BNC have gained attraction in the food industry as food packaging material and additive over the recent year due to special features, current environmental issues, and increased interest in the use of renewable resources. BNC and its derivatives have many tailor-made specifications including high water and oil-retention capacity in the wet BNC form (more than 200 times of its dry weight), hydroxyl groups, thermal stability, and crystallinity with excellent mechanical properties for cheese applications. Various forms of BNC including wet, freeze-dried, and air-dried BNC film as well NF-BNC and NC-BNC in both suspension and powder forms are presently available on the market for food application. Despite many practical properties, only some selected works have focused on cheese applications of BNC, therefore, a new horizon is expected for the application of BNC in cheese. In this article, in addition to discussing the current limited application of BNC in the cheese industry, we have also identified many potential future applications of BNC. BNC and its derivatives can be used on cheese packaging or as an additive for new fiber-rich cheese formulations. Additional comprehensive study is also needed to investigate the role of BNC on cheese coagulation, manufacturing, textural/sensory features and optimize the exact level of BNC in each cheese type.

Conflicts of interest

None.

Disclaimer

Non.

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