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Review

Nanocellulose in food packaging: A review

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ABSTRACT

The research in eco-friendly and sustainable materials for packaging applications with enhanced barrier, thermo-mechanical, rheological and anti-bacterial properties has accelerated in the last decade. Last decade has witnessed immense interest in employing nanocellulose (NC) as a sustainable and biodegradable alternative to the current synthetic packaging barrier films. This review article gathers the research information on NC as a choice for food packaging material. It reviews on the employment of NC and its various forms including its chemico-physical treatments into bio/polymers and its impact on the performance of nanocomposites for food packaging application. The review reveals the fact that the research trends towards NC based materials are quite promising for Active Packaging (AP) applications, including the Controlled Release Packaging (CRP) and Responsive Packaging (RP). Finally, it summarizes with the challenges of sustainable packaging, gray areas that need an improvement/focus in order to commercially exploit this wonderful material for packaging application.

1. Introduction

Whether be it the prevention of physical damage, external contamination or deterioration, packaging is necessary for the protection of goods (Wang & Wang, 2017). Effective packaging apart from physical protection offers conservation of the quality and safety of the food during transportation and storage. The shelf life of the food product can be extended chiefly by preventing- i) permeation of moisture, various gases including oxygen, carbon dioxide, ii) exposure to light, iii) deterioration by micro-organisms. Traditional materials like glass, aluminum, tin, petro-based polymers impart requisite strength and barrier properties but offers economic and ecological setbacks.

There has been an increase in demand for packaging materials which are non-petroleum based, biodegradable, pose very minimal threat to environment and are manufactured from sustainable and renewable resources (Han, Yu, & Wang, 2018). Burgos et al. presented the need of biodegradable polymers to replace the petro-based synthetic polymers as raw materials for wrapping (Burgos, Tolaguera, Fiori, & Jiménez, 2014). Conventionally used synthetic polymers have an edge over the biopolymers. Biopolymers have poor barrier, thermal and mechanical properties compared to their synthetic counterparts (Jabeen, Majid, & Nayik, 2015). This limits their usage in commercial applications such as food packaging. Partial solution to these concerns is crosslinking, grafting or functionalization of the monomers (Hambardzumyan et al., 2015). poly(lactic acid) (PLA) (Ahmed & Varshney, 2011), polyhydroxyalkanoates (PHAs) (Panaitescu, Frone, & Chiulan, 2016; Yu, Yan, & Yao, 2014), chitosan (El Miri et al., 2015), proteins obtained from animals (gelatin, caseinates, etc.) and vegetables (soy, gluten, etc.) are among the widely studied biodegradable and bio-based polymers for food packaging (Peelman et al., 2015). It is possible to improve the chemical and structural properties of biopolymers by addition of reinforcing agents, making them eligible for commercial applications.

Recent years have seen increased attraction towards the nanotechnological applications in packaging (Huang, Li, & Zhou, 2015). Nanofillers are fillers or additives with their size lying in the range of 100 nm (Poole & Owens, 2003). These nanofillers are used in improving the properties of polymeric material in a composite for desired applications. Different thin composite films produced using nanofillers have vast applications in coating, packaging, as they provide impermeability towards moisture, gases such as oxygen, carbon dioxide and aromas, etc. and have good antibacterial properties as well. Such properties of the films ensure the packed foods last long. Nanocellulose (NC), prepared by breaking down cellulose fibers, is one such biodegradable, renewable nanofiller (biopolymer) that produces low carbon footprint. Plants create around 75 billion tons of cellulose every year, making this an extremely abundant material (Feng et al., 2018). For cellulose derived packaging, three types of cellulose are used, namely, cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), and bacterial nanocellulose

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(BNC). Table 1 shows the comparative properties of these cellulose types. The details of production of NC including its pretreatment and isolation, technologies for production is not the part of our discussion and is elaborated elsewhere (Abdul Khalil et al., 2016; Ferrer, Pal, & Hubbe, 2017). Currently, CNC and CNF are incorporated as reinforcing agents into various biopolymers for making green composites (Moustafa, Youssef, Darwish, & Abou-Kandil, 2019). In recent past, these nanomaterials have been increasingly employed in packaging applications. NC can synergistically work with other materials to enhance barrier, thermo-mechanical, and rheological properties of the nanocomposite. Intermolecular and intramolecular hydrogen bonding makes cellulose insoluble in almost all solvents as these bonds impart high strength to it. Research has also commenced towards the recycling of this NC (Shanmugam, Doosthosseini, Varanasi, Garnier, & Batchelor, 2019) (Table 2) and employing waste paper as a source to extract it further (Kumar, Pathak, & Bhardwaj, 2020). It has been reported that the films produced from NC can be voluntarily recycled and reprocessed into a packaging film without drastically degrading the properties of the same (Shanmugam et al., 2019). The foremost reason behind this would be its carbon neutrality, non-toxic nature, recyclability and sustainability (Vilarinho, Sanches Silva, Vaz, & Farinha, 2018). Attributed to the distinctive properties of NC, tunable surface chemistry, barrier

properties, mechanical strength, crystallinity, biodegradability and non-toxicity, high aspect ratio, it is an arising credible renewable green substrate for food packaging applications (Ferrer et al., 2017; Lacroix, Criado, Fraschini, & Salmieri, 2014). Fig. 1 shows the number of SCI indexed journals published employing NC in packaging applications. Number of patents on NC granted demonstrates its overall growing importance in coming future (SciFinder Scholar database, Nov. 2020). Research in the production of eco-friendly bio-nanocomposites for application in the food packaging sector has stimulated recently (Berthet, Angellier-Coussy, Guillard, & Gontard, 2016; Criado et al., 2014; Dhar, Bhardwaj, Kumar, & Katiyar, 2015; Hambardzumyan et al., 2015; Sanchez-Garcia, Lopez-Rubio, & Lagaron, 2010; Takala et al., 2013). Such composite films have also been made and tested for applications including intelligent packaging,(Abdul Khalil et al., 2016) see-through packaging (Azeredo, Rosa, & Mattoso, 2017), UV screening packaging (Boufi et al., 2016), antimicrobial packaging (Osong, Norgren, & Engstrand, 2016), etc. using different bio-polymeric matrices such as agar (Reddy & Rhim, 2014; Shankar & Rhim, 2016), chitosan (Dehnad, Mirzaei, Emam-Djomeh, Jafari, & Dadashi, 2014), carboxymethyl cellulose (CMC) (Benyoussif et al., 2015), polyvinyl alcohol (PVA) (Ching, Rahman, Ching, Sukiman, & Cheng, 2015; Lani, Ngadi, Johari, & Jusoh, 2014). The NC composites are a green option for manufacturing packaging materials (Sharma, Thakur, Bhattacharya, Mandal, & Goswami, 2019). The plenty of hydroxyl groups present on the surface of NC allows its chemical crosslinking with different polymers and thereby strengthen

Table 1
Comparative properties of various NC including CNC, CNF, and BNC.

Properties	CNC	CNF	BNC	References
Dimensions (nm)	L: 100-400 D: 3-40	L: 700-2000 D: 6-80	L: 100 - >1000 D: 30-60	
Elastic Modulus (GPa)	130-250	20-60	15-138	(Rajinipriya, Nagalakshmaiah, Robert, & Elkoun, 2018); (Kargarzadeh et al., 2018); (Rol, Belgacem, Gandini, & Bras, 2019); (Klemm et al., 2018)
Tensile Strength (MPa)	7500-7700	350-500	20-2000	
Thermal stability up to (°C)	220	260	300	
Crystallinity (%)	60 to 90	40-70	50-60	
Transparency (%)	> 90	80-90	> 90	

Table 2
Recent research in improving the water vapor barrier properties.

Composite	Concentration	WVTR (g $m^{-1}s^{-1}$ Pa^{-1}) x10^{-11}	Authors
Cellulose as matrix phase			
Unused NC film		5.45	(Shanmugam et al., 2019)
Recycled NC film		12.90	
Bismuth complex / MFC sheet	Bismuth Complex – 0.1–2 wt.%	3 – 3.5	(Maliha et al., 2020)
Cellulose as reinforcing phase			
CNC incorporated in PLA with PEE and TBE as additives (1 wt.% of CNC)		1.98	(Khodayari et al., 2019)
	1 v/v% PEE	2.00	
	1 v/v% TBE	2.06	
Chitosan crosslinked with CMC as matrix and CNC as reinforcing phase	0 wt.%	0.15	(Chi & Catchmark, 2018)
	5 wt.%	0.13	
	10 wt.%	0.09	
C-CNC whiskers in Cassia-gum	0 wt.%	34.66	(Cao et al., 2020)
	4 wt.%	25.05	
	6 wt.%	26.12	
Bacterial Celulose (BC)-PVA-Glycerol films with varying concentration of the PVA and Glycerol	PVOH – 0 wt.% Glycerol – 0 wt.%	2.38	(Cazón et al., 2020)
	PVOH – 2.5 wt.% Glycerol – 0 wt.%	1.87	
	PVOH – 0 wt.% Glycerol – 2.5 wt.%	5.92	
	PVOH – 2.5 wt.% Glycerol – 2.5 wt.%	17.20	
MCC incorporated in PVA with AgNPs	MCC – 16 wt.%	37.39 g/m2h	(Sarwar et al., 2018)
	AgNPs – 5 wt.%, MCC – 16 wt.%	14.36 g/m2h	
Alginate and CNF complex prepared by blending	CNF – 9 wt.%	26.70	(Zhao et al., 2020)
Prepared by layer by layer formation	CNF – 9 wt.%	26.10	
Chitosan and CNF composite Prepared by blending	CNF – 9 wt.%	196.70	
Prepared by layer by layer formation	CNF – 9 wt.%	28.90	
CNC extracted from Bamboo incorporated into Corn starch matrix	4 wt.%	4.25	(Chen et al., 2019)

the composites further.

This review throws light on the advancement of NC reinforced bio/polymer nanocomposites for packaging application. It emphasizes on the property enhancement like impermeability of various gases and water vapor, transparency; improving resistance towards UV light, oxidants, micro-organisms, etc. of such nanocomposite films.

2. Gas barrier properties

Oxygen barrier is important in food packaging as its presence assists the aerobic microorganisms to spoil the food and lose its nutritional properties. In order to extend the shelf-life of the food, it is required to maintain low oxygen environment. NC has an ability to form hydrogen bonds (with itself as well as with other biopolymers) that forms a dense network. This impedes various gas molecules to pass through due to small pore size. Apart from that, its high crystalline regions are impermeable to gases, making it a good candidate to impart gas barrier properties. Permeability of gas depends upon the dissolution of gas and its diffusion rate in the packaged film (Wang, Gardner et al., 2018). NC increases the diffusion path length of the gases (or water vapor) that permeate the packaging as shown in Fig. 2 (Nair, Zhu, Deng, & Ragauskas, 2014). It is worth noting that, up to a relative humidity (RH) level of about 70 %, the hydrogen bonding reduces the gas permeability because of the increase in cohesion (Mascheroni et al., 2016; Rampazzo et al., 2017; Sukyai et al., 2018). As the RH value increases further, the

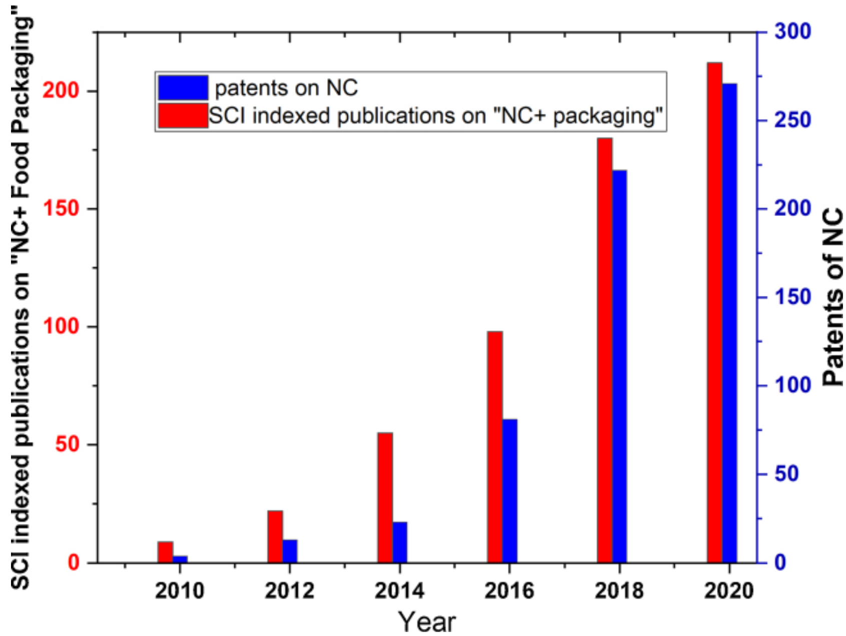

Fig. 1. Growing importance of NC reflects in increasing the number of SCI indexed publications and patents granted over the last decade.

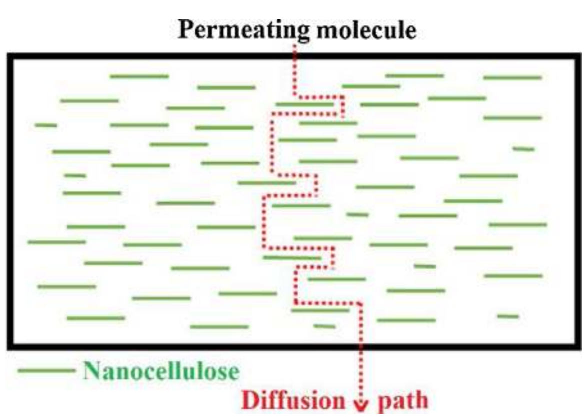

Fig. 2. Diagram showing the increase in diffusion path of the permeating molecule due to the presence of NC (Nair et al., 2014).

moisture (and hence gases too) in the surroundings, begins to diffuse into the polymer. Thus, it can be inferred that the atmospheric conditions need to be taken into consideration while designing the packaging material.

Improved barrier properties with respect to packaging of food requiring less moisture content for instance nuts, dried fruits, and spices, etc. have been obtained through multilayer packaging. CNFs were layered on polyethylene terephthalate (PET) and the resulting film was further coated with low-density polyethylene (LDPE) via extrusion, giving a three-layered structure (Vartiainen, Kaijunen, Nykanen, Maim, & Tammelin, 2014). The barrier performance of this multilayered film was better than the commercial ethylene vinyl alcohol multi-layered barrier film. With increasing grammage of CNF (from 1 to 7 g/m^2) coating on paper, the air permeance and oxygen permeability (OP) of the paper was reduced by almost 70 % and 10^4 times respectively (Aulin, Gällstedt, & Lindström, 2010; Lavoine, Desloges, Khelifi, & Bras, 2014). Coating on a paper is important to increase the barrier properties and moisture resistance. Addition of CNF coating also increased tensile strength and oil resistance. Missio et al. (Missio et al., 2018), in their work, used condensed tannin and CNFs, where CNFs contributed to the mechanical properties and tannin served as an antioxidant (Duval & Avérous, 2016). Antioxidants mitigate the oxidation kinetics of the food, even in presence of oxygen. The prepared composite had better surface hydrophobicity as well as high density resulting in an excellent 6-fold increase in barrier properties towards air when compared to a pure CNF film (19.27 mL/min) and 90-folds when compared to a regular A4 size paper (277.2 mL/min). The resistance towards air was about 3.1 mL/min, which is close to that of plastic packaging for chocolate made from poly-propylene. The film produced also manages to overcome the shortcoming of NC film, wherein the density of the film needs to be compromised in order to decrease the affinity towards water, thereby degrading the barrier properties (Hubbe et al., 2017).

Earlier, Belbekhouche et al. reported that the gas permeability in CNF films was lesser than in CNC films (Belbekhouche et al., 2011). Formation of dense entanglements by the CNF network films was attributed to lesser permeation of gases through it. It was observed that the CNF films displayed Oxygen Transmission Rate (OTR) of approximately 17 mL/m^2/day (Syverud & Stenius, 2009) (see Fig. 5), which is equivalent to many petro-based polymers (Parry, 1993). Mondragon et al. fabricated a film involving gelatin matrix and reinforcing phase of CNFs and CNCs separately. The OTR through gelatin was reduced by 21 % and 36 % at 5 and 10 wt.% concentration of NC (similar effects were observed employing CNC and CNFs), respectively (Mondragon, Peña-Rodriguez, González, Eceiza, & Arbelaiz, 2015). However, Higher is the crystallinity of the film; higher is the gas barrier property. Compared to other types of NC (CNFs or BNCs), CNCs have highest degree of crystallinity, providing better barrier to gas molecules. Dhar et al. reported that just 2 % CNC in poly(3-hydroxybutyrate) (PHB) reduced the oxygen permeability of PHB films by 65 % (Dhar et al., 2015). The improvement in barrier properties is dependent on the concentration of CNC. It is preferential to incorporate the CNCs into the bulk of the polymer to obstruct the diffusion of gases through the composite (Karkhanis, Stark, Matuana, & Sabo, 2018; Luzi et al., 2016). CNC has proven its worth as an oxygen barrier material, when incorporated into kappa carrageenan (Azizi and Mohamad, 2018), collagen (Long et al., 2018), poly(propylene carbonate) (PPC) with polyethylene glycol (PEG),(Jiang, Zhang, Feng, Zhang, & Wang, 2017) poly(L-lactic acid) (PLLA) (Kakroodi, Kazemi, Nofar, & Park, 2017), CNC has also shown great impermeability towards oxygen as a coating on PET (Rampazzo et al., 2017). Despite of the fact that, high crystallinity of CNCs results in least OTR, the films or coatings prepared from CNFs are less brittle than that prepared from CNCs.

The property of NC of being tortuous, which in turn reduces the permeation of the gas molecules through composite films, is worth studying in future (Ferrer et al., 2017). The free spaces between the molecules, and the cohesive energy density of the same also determine the gas permeability of a material (Miller & Krochta, 1997). When CNCs are incorporated into a matrix, high cohesion energy density is observed due to the presence of a network of hydrogen bonds. Also, the free volume is less and the chain mobility is reduced attributed to the presence of nanoparticles (Lagaron, Catalá, & Gavara, 2004; Sharma & Dhanjal, 2016). Fig. 3 displays how the oxygen barrier properties (OBP) of poly(L-lactic acid) (PLLA) vary with addition of functionalized CNC (Li, Bao et al., 2019). The oxygen permeability of neat PLLA was reduced by 66.4 % on the addition of PEG (1 g) and CNC (0.5 wt.%). (2,2,6, 6-Tetramethylpiperidin-1-yl)oxyl (TEMPO)-oxidized CNCs have also been testified to act as oxygen barriers (Vähä-Nissi et al., 2017). Tyagi et al. prepared a film, a composite system of CNC and CNF, which decreased the OTR by a factor of around 260 and air resistance increased by a factor of 300, relative to an uncoated paper (Tyagi, Lucia, Hubbe, & Pal, 2019). Also, the increase in grease and oil resistance was analogous to that of the fluorochemicals. Fluorochemicals, because of their credible lipophobic and hydrophobic properties, are a good raw material for waterproof and non-stick food packaging (Schaider et al., 2017).

3. Water vapor barrier properties

The water vapor (WV) permeation into the film is an important concern as it directly affects the transmission of oxygen through the film. It has been reported that, at a relative humidity level of 80 %, the OTR was increased 20 times (Cozzolino, Campanella, Türe, Olsson, & Farris, 2016). The presence of water plasticizes the film. The gas diffusion rate upsurges as the water molecules weaken the film cohesion at higher humidity levels (Lagaron et al., 2004). Factors that affect the water vapor transmission rate (WVTR) of a packaged polymer/composite film are pressure, temperature, crystallinity (the diffusion and sorption predominantly take place in the amorphous region of a polymer) and hydrophilicity (polysaccharides are hydrophilic in nature), film density and thickness, pore size and structure. For a film to increase the shelf life of a food product, it needs to avoid the moisture interaction during the film handling, transportation and application. Research is exhaustively being carried out employing NC either in coating, or as a filler in a composite film or as a matrix alone.

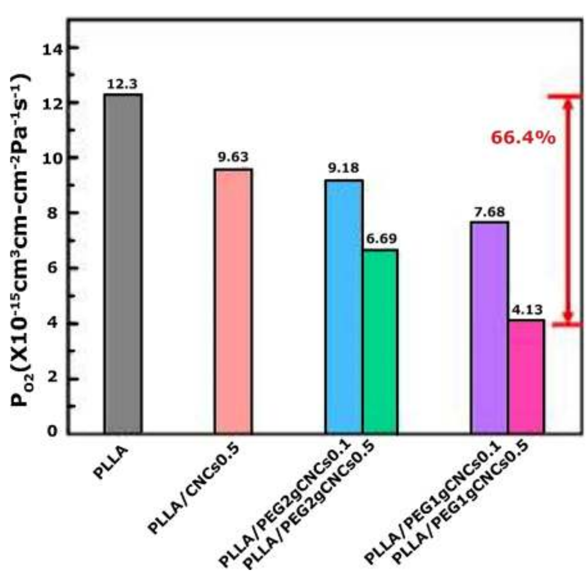

Fig. 3. Oxygen barrier properties of CNC (functionalized) with Dopamine induced polyethylene glycol) incorporated in poly(L-lactic acid) biocomposite. (L. Li et al., 2019).

3.1. Films based on Cellulose Nanofibrils

The barrier properties of NC films are good for gases but are very poor for WV when used in its unmodified form. The WVTR of CNF film was found approximately 174 g/m^2/day (Rodionova, Lenes, Eriksen, & Gregersen, 2011) and is very high compared with LDPE (~ 15−20 g/m^2/day) (Parry, 1993). Consistent efforts are on in improving water vapor barrier properties (WVBP). Sharma et al. heated the CNF films at 175 °C for 3 h and observed 50 % reduction in WV permeability (Sharma et al., 2014). Heating caused an increase in the crystallinity and hydrophobicity of CNF and reduction in porosity that hinders the diffusion of water molecules. Modified CNF, having high specific area and aspect ratio, gives entanglement ability with the network (B. Wu et al., 2017). However, TEMPO oxidized CNF (TOCN) falls short when talked about its water barrier properties (~ 235 g/m^2/day for 50 % RH), even though its performance as a barrier against gases is comparable to synthetic polymers (See Fig. 5). Bideau et al. synthesized TOCN, PVA and Polypyrrole (PPy) nanocomposite films by two ways. i) *in-situ* by chemical polymerization (Bideau, Bras, Saini, Daneault, & Loranger, 2016) and also ii), distributed pyrrole over this TOCN/PVA film and allowed it to polymerize (Bideau, Bras, Adoui, Loranger, & Daneault, 2017). In the second processing case, the performance of the film was tested against gas and WVBP. PPy, being hydrophobic and at the outer layer, protects the film from water permeation (18 g/m^2/day). This film's performance was similar to the commercially available petro-based polymers. (16.8 g/m^2/day). In the first case, it was observed through EDX studies that PPy located on the composite surface, resulting in increased contact angle from 54.5 to 83° and corresponding increased heat protection. The performance of this film was evaluated against food containing bacteria *(B. Subtilis* and *EscherichiaColi*). It was demonstrated that by slight leaching of PPy, this film acted as an active packaging on meat and killed the bacteria by contact.

Recently, research is being focused on preparing a coating of NC onto biopolymers, thereby making the packaging completely biodegradable. NC being dispersible, an aqueous coating can be applied as a pure thin layer or as a composite with other commonly used materials. CNFs has also been used as an edible coating on fruits, for instance, coating of aqueous slurries of CNF and calcium carbonate nanoparticles onto blueberries (Zhao, Simonsen, Cavender, Jung, & Fuchigami, 2014), or coating on strawberries with a mixture of 1 % chitosan and 5 % NC (Dong, Li, Liu, & Zhu, 2015). These coatings proved to be useful in reducing the leakage of anthocyanins, weight loss and decay rates. The use of paperboards for packaging, aims at extending the shelf life of the packaged food while reducing the packaging waste (Silvestre, Duraccio, & Cimmino, 2011). However, the use of paperboards alone for food packaging is not desirable due to its weak mechanical properties and its susceptibility to humidity (Biedermann-Brem, Biedermann, & Grob, 2016). The emergence of paperboards as a substrate for protective coatings was reviewed by Park (Park, 2005). Water vapor permeation rate can possibly be reduced via making a multi-layered system, which would protect the substance inside from the effects of moisture (Schade, Weinkoetz, & Assmann, 2015; Jari Vartiainen et al., 2016) over a substrate. One such multi-layered packaging was formulated by Koppolu et al. (Koppolu et al., 2019). The authors developed a thin multilayer coating of NC reinforced PLA over a paperboard via slot-die coating and extrusion coating (Fig. 4(a)) (Koppolu et al., 2018; Kumar, Elfving, Koivula, Bousfield, & Toivakka, 2016). It lowered WVTR by 23 % even at 90 % humidity, at 38 °C, reduced OTR and heptane transmission rate by 98 % and 99 %, compared to PLA-coated paperboard and the paperboard alone respectively. PLA compensated for the poor water vapor resistance of NC. In their work, Bideau et al. emphasized on the use of PPy and TOCN coating. The coating was tested and compared with an uncoated paperboard by storing cherry tomatoes for 10 days (Fig. 4(b)). The tomatoes kept inside the coated paperboard retained

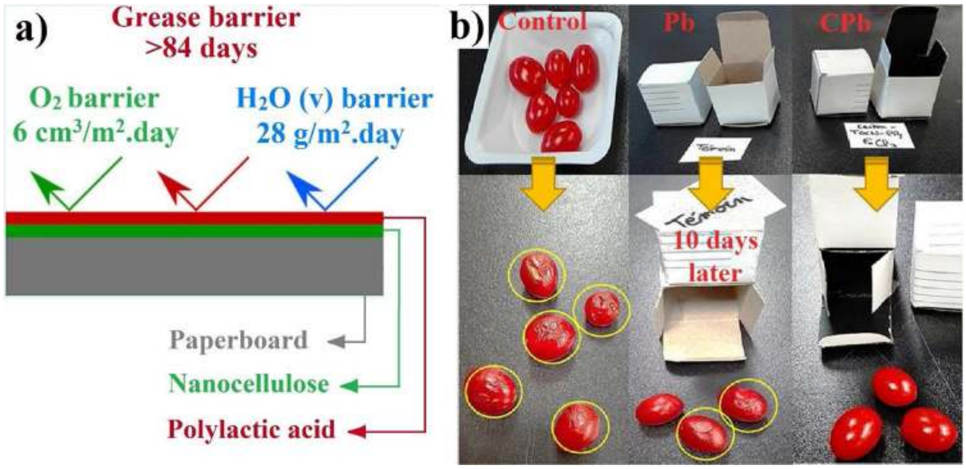

Fig. 4. (a) A diagrammatic representation of multilayered packaging system restricting grease, O_2 and H_2O (reproduced from (Koppolu et al., 2019)) (b) Packaging simulation of Cherry tomatoes in coated and uncoated paperboard for 10 days. (Reproduced from (Bideau et al., 2018)).

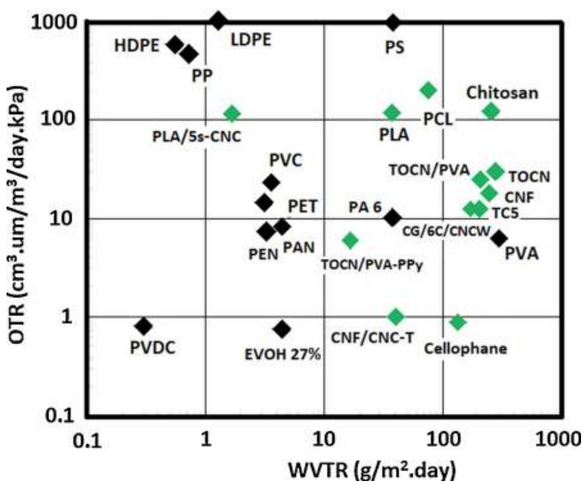

Fig. 5. WVTR and Oxygen transmission rate (OTR) Synthetic polymers compared to that of the Biopolymers and composite packaging films.(Bardet et al., 2015; Cao et al., 2020; Fortunati, Peltzer, et al., 2012b; Ma et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
Adapted from (Bideau et al., 2017) (Dark Points – Petro-based Polymers, Green Points - Biopolymers).

their texture and stayed firm. The dense network formed by the combination of TOCN and PPy, providing a barrier against moisture and oxygen, was responsible for the same. The authors also suggested that the 80 % of the paperboard could be reused by removing the layer of PPy.(Bideau, Loranger, & Daneault, 2018)

3.2. *Films based on Cellulose Nanocrytals*

Similar to CNFs, CNCs have been employed as coatings for packaging application. Azeredo et al. compared the reinforcing ability of CNC derived from coconut fiber on alginate-acerola puree-based coatings (Azeredo, Miranda, Ribeiro, Rosa, & Nascimento, 2012). A test was carried out over a period of 7 days by comparing the properties of acerola before and after this interval. The CNC reinforced film decreased the Water Vapor Permeability (WVP), fruit weight loss, ascorbic acid loss, and decay incidence by 30 %, 53 %, 70 %, and 46 %, respectively. The performance of CNC reinforced coating was comparable to Montmorillonite nanoclay reinforced coating, while the latter providing better fruit weight retention. Pertaining to more recent studies, CNCs have broadly been used as fillers in biopolymeric matrices for fabricating composite packaging films. Even though CNC and most of the biopolymers are hydrophilic in nature, it has proven that the resultant nanocomposite imparted increased WVBP to various biopolymer matrices (Dhar et al., 2015; George & Siddaramaiah, 2012). Formation of hydrogen bonds between the CNC and various biopolymers not only improve the cohesiveness of the film but also does not make O—H groups available for water permeation. Added to that, high crystallinity of CNC increases the thermo-mechanical properties of the nanocomposite film (Huq et al., 2012).

Homogeneous dispersion of NC into biopolymer matrix is to be ensured to enhance WVBP and OBP. One of the possible ways is to use surfactants which does not only avoid agglomeration of CNC but also act as a compatibilizer between NC and the hydrophobic matrix. Fortunati et al. compared pristine CNC-PLA with surfactant-modified CNC-PLA nanocomposites.(Fortunati, Peltzer et al., 2012) Increased dispersion of CNC and its interaction with PLA enhanced the barrier properties of the film. 1 % surfactant in the nanocomposite film formulation reduced WVP and OP by 34 % and 26 % respectively. Composites having CNC as a filler have been evidenced to have reduced water vapor permeability (WVP) and better moisture barrier properties (Paunonen, 2013). It has been testified that NC reinforced cassava starch film showed reduced WVP and increased tensile strength (Santana et al., 2019). Incorporation of NC into polysaccharides or biodegradable polymer matrices, also results in lowering down of WVP (Wang, Gardner et al., 2018).

Chi et al. (Chi & Catchmark, 2018) prepared a ternary polysaccharide polyelectrolyte complex (PPC) material via high-shear homogenization, from CMC, CS and CNC. CNC was ionically cross-linked to CMC/chitosan matrix. At 10 wt% of CNC, the Young's modulus and tensile strength were 4.7 GPa and 60.6 MPa, respectively, 60 % and 48 % higher than for the PPC film without CNC, along with a WVTR of 7982 g μm m^{-2} d^{-1}, 40 % lesser than when no CNC was added (Table 2). The PPC material provided an impeccable barrier against grease, oil and water penetration, for up to one week, on a paperboard substrate at <5 wt% CNC concentration in agreement to previous studies (Basu, Plucinski, & Catchmark, 2017; Dai et al., 2017). The WVTR was reduced due to two reasons. Firstly, The PPC matrix (CMC/chitosan) forms a dense packed structure, refusing the water vapor diffusion. Secondly, highly crystalline CNC strengthens the interaction with the matrix (Azeredo et al., 2017; Saxena & Ragauskas, 2009). Considering a comparative study of the food packaging properties of a composite prepared from different non-wood sources of NC, Chen et al. used bamboo, sisal and cotton linters for their study (Chen, Liu, & Chen, 2019) (Table 2). The matrix chosen was starch, found to be significantly eco-friendly.(Bonilla, Atarés, Vargas, & Chiralt, 2013) It was observed that bamboo derived NC/starch film showed the most reduced permeation towards WV and oxygen permeability, reduced by about 27.6 % and 32.9 %, respectively, when compared with the pure starch film. The reduction in the permeabilities was attributed to the higher crystallinity of the bamboo derived NC compared with sisal and cotton derived NC (Kaushik & Kaur, 2016). Table 2 displays the WVBP of NC-based composites in this section with varying concentration of constituents.

4. UV-barrier and antioxidant properties

UV radiations in the range 315−400 nm (termed as UVA) and 280−315 nm (UVB——) cause extensive photochemical reactions, which result in free radical formation. The free radicals further cause oxidation of lipids, proteins and vitamins, alongside, the degradation of antioxidants, change in color and texture and formation of off-flavors. Thus, exposure to UV radiation leads to loss of nutritional and organoleptic properties, reducing the shelf-life and quality of the food products (Lázaro et al., 2014; Olarte, Sanz, Federico Echávarri, & Ayala, 2009; Sadeghifar, Venditti, Jur, Gorga, & Pawlak, 2017). This highlights the importance of radical scavenging and antioxidant properties in food packaging applications (López de Dicastillo et al., 2011). PPy, a conjugated polymer, has antioxidant properties. Bideau et al. formed a composite film of NC/PPy and observed very less oxygen permeability (16.5 cm^3/m^2/day). At the same time, this film preserved bananas for five days without any sign of oxidation (Bideau et al., 2017). In another work, Bao et al. reported that the nanocomposite film formed with Chitosan-xylan-CNC displayed good antibacterial, antioxidant and mechanical properties wherein xylan acted as antioxidative agent (Bao et al., 2018). Similarly, Wang et al. employed epigallocatechin-3-gallate as an antioxidative agent in chitosan-BC nanocomposite and reported similar results (Wang, Xie et al., 2018). Luo et al. imitated paper-making process and fabricated aramid nanofibers (ANF)/CNF nanocomposite (Luo et al., 2019). Pure CNF displayed high optical transmittance (400−800 nm) but the UV shielding was poor as absorbance was quite low (200−400 nm). Aramid nanofibers can absorb UV rays due to conjugation effect of benzenes and amide bonds and show high transmittance in the visible spectrum. CNF film containing 2 % ANF showed excellent UV shielding with high transparency. ANFs have large number of active groups on its surface, thereby making interfacial bonding with cellulose matrix possible. Strong CNF films can also be developed via spray coating (Shanmugam, Varanasi, Garnier, & Batchelor, 2017), or vacuum filtration (Fang et al., 2020).

Antioxidants can be combined with the food directly but are preferred to be incorporated into the packaging film.(Mastromatteo, Mastromatteo, Conte, & Del Nobile, 2010) Such films containing polyphenols like grape seed extract, murta leaft extracts, thyme extracts etc. have been employed to resist food from oxidation (Silva-Weiss, Bifani, Ihl, Sobral, & Gómez-Guillén, 2013; Talón et al., 2017), Wu et al. synthesized a multifunctional film containing TOCN immobilized silver nanoparticles (AgNPs) with grape seed extracts (GSE) (Wu, Deng, Luo, & Deng, 2019). It was observed that the film developed UV shielding, reduced transparency, antioxidant properties (due to GSE) along with increased shelf life due slower rate of release (only 5.7 % in 14 days) of antibacterial AgNPs. A biohybrid film was produced by combining anionic tannin extracts and cationic CNFs (CCNFs) (Li, Sirviö, Haapala, Khakalo, & Liimatainen, 2019). Better absorbance of UV radiations was observed by adding more tannin compounds due to the increase in polyphenolics in the film. CCNF (90 wt.%) and Tannin (10 wt.%) absorbed almost 100 % of the UV radiations (wavelength $<$ 320 nm) whereas, CCNF (95 %) and Tannin (5 wt.%) absorbed 92 % of the radiations in the same range (Fig. 6c & d). Tannin extracts also helped reducing the haziness in the film. The antioxidant properties of the film were assessed by 2, 2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging test (Byun, Kim, & Whiteside, 2010). According to the test results, the color of the DPPH radical faded gradually due to its reaction with antioxidants. This also resulted in decreasing UV-light absorbance at 517 nm.

Cazón et al. prepared a composite by the addition of PVA and glycerol to BC films (Cazón, Velazquez, & Vázquez, 2020). The UV light (200−280 nm) transmittance of pure BC films was as low as 1 % and about 7.5 % at 400 nm (Fig. 6a, Table 2). The UV light transmittance of the BC films was further decreased to 0.57 % at 200−280 nm, on the addition of glycerol and reached a maximum value of 7.5 % at 400 nm. The transmittance of the above two films were found to be better than regenerated cellulose films and regenerated cellulose-glycerol-PVA films, respectively (Cazón, Vázquez, & Velazquez, 2018; Cazón, Vázquez, & Velazquez, 2018; Cazón, Velazquez, & Vázquez, 2019). The addition of glycerol imparted plasticizing effect (Young's modulus

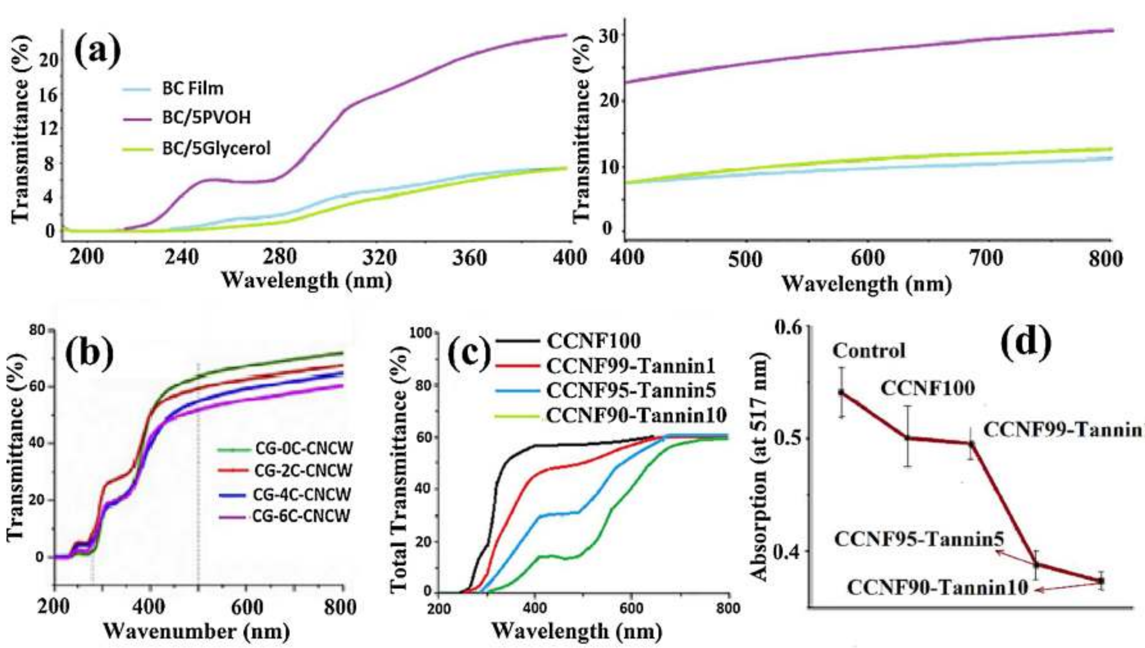

Fig. 6. (a) UV–vis Spectra of BC film, BC-5 % PVA, BC-5 % Glycerol; (Cazón et al., 2020) (b) UV–vis Spectra of CG/C-CNCW films at different C-CNCW concentrations; (Cao et al., 2020) (c),(d) UV-light transmittance and absorbance through CCNF-Tannin films.(P. Li et al., 2019).

decreased by 98.8 % at 5 wt.% glycerol) on the composite while PVA was found to improve the mechanical properties (Young's modulus improved by 17 % at 5 wt.% PVA).

Cao et al. reinforced edible packaging film with carboxylated CNC whiskers (C-CNCW), to be potentially used as oil bags (Cao et al., 2020). (Fig. 5) The UV–vis spectra of the film was studied showing that UV light (200−280 nm) barely transmitted through the film.(Fig. 6 b) The sealing ability of the film was an exceptional 1295.40 N/m for pure Cassian Gum (CG) film and 2218.78 N/m (CG-4 % C-CNCW). These values are much higher compared to a recently produced gelatin based films having a seal strength of 500−870 N/m (Ciannamea, Castillo, Barbosa, & De Angelis, 2018). It was also observed that the addition of C-CNCW to the CG films hardly affected its optical transparency. Due to low aspect ratio, CNC has less effect on transparency which is advantageous for food packaging application.

5. Active packaging

Antimicrobial effect, WVBP and antioxidant capacity are important characteristics of active packaging (AP) (Dainelli, Gontard, Spyropoulos, Zondervan-van den Beuken, & Tobback, 2008). Antibacterial active packaging aims at reduction or rather hindering the growth of bacteria, maintaining and increasing the shelf life of the food products (Benito-Peña et al., 2016; Lavoine, Desloges, Manship, & Bras, 2015). The introduction of antimicrobial compounds into the food packaging, directly or indirectly, can prove to be beneficial.

NC ensures high loading of the antimicrobial agents because of its high surface area. The following factors have promoted the use of cellulose in active packaging – (i) It is stable in water, thereby reduces use of organic solvents; (ii) Target surface functionalization on a vast scale favors anchoring and selective growth of nanoparticles (NPs). iii) Assist in the controlled release of bioactive compounds, into the packed food, which are encapsulated inside biopolymers. In other words, it acts as a carrier of antioxidant, antimicrobial and antifungal compounds (Fortunati, Armentano et al., 2012). Both, the compounds and NC, form essential components of active food packaging. The structure of the biofilms can be altered using CNC in order to enable better controlled release of antimicrobial agent.

The foremost advantage of active packaging is that the active biocides delivered inside the packaging, lengthens the shelf life or service life of the food. Active packaging reduces, and thereafter, prevents the proliferation of food spoiling microorganisms (Ribeiro-Santos, Andrade, & Sanches-Silva, 2017). From the studies of kapetanakou et al. and Appendini et al. (Appendini & Hotchkiss, 2002; Kapetanakou & Skandamis, 2016), it can be inferred that there are three different ways of introducing active biocides into food packaging, as shown in Fig. 7 (Gan & Chow, 2018).

The traditional way of preventing colonization on food surface by unwanted micro-organisms is to add antimicrobial agents directly into the food formulation either by dipping or spraying techniques-(Fig. 7, concept 3). However, it causes inactivation of antimicrobials due to its rapid migration into the bulk of the food (Quintavalla & Vicini, 2002). The growth of micro-organisms occur mostly on the surface of the food. Hence, it is a good idea to release antimicrobials from the packaging film that not only controls the rate of release but also does not change the taste of food which otherwise is possible due to direct contact (Nguyen Van Long, Joly, & Dantigny, 2016). First concept can be often seen in meat packaging, whereas in concept 2, antimicrobial compounds are incorporated into the biopolymeric matrices. Bacteriocins, essential oils or polyphenols are mostly incorporated into packaging films to impart antimicrobial properties in it. Nisin is the only bacteriocin (antimicrobial peptide) which is permitted as a food preservative. In a nutshell, AP can be categorized into non-migratory (Responsive Packaging) and migratory AP (Controlled Release Packaging), categorized on the basis of release of antimicrobial agents in the packaged environment. Responsive packaging inhibits the growth of food spoiling bacteria without the actual migration of antimicrobials to the packed food (Hosseinnejad, 2014). It also draws out a desirable response from the food packaging system, enabling the real-time monitoring of food quality (Brockgreitens & Abbas, 2016). Devised by LaCoste et al. (LaCoste, Schaich, Zumbrunnen, & Yam, 2005), the term CRP refers to a packaging designed specifically for the timed release of specific objects in order to maintain the safety and quality of the food for longer period of time. These two terms, CRP and Responsive AP, are supposedly the future of AP applications.

5.1. Controlled release packaging (CRP)

Both organic and inorganic materials can be used as antimicrobial agents in composites for food packaging. Compared to the organic

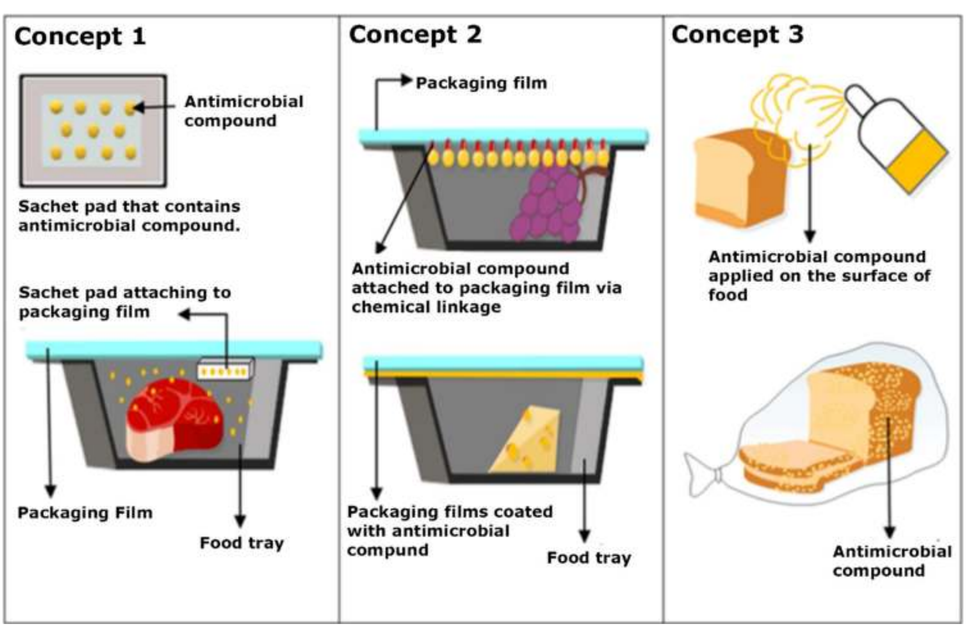

Fig. 7. Concept 1 - No contact between the food and antimicrobials; Concept 2 – Antimicrobials and food in indirect contact; Concept 3 – Both the components in direct contact.(Gan & Chow, 2018).

materials, inorganic materials such as metal oxides or metal nanoparticles, have better thermal stability; thus, can withstand more intense processing conditions. Fig. 10 graphically shows the bacterial inhibition zone thickness, produced by action of antimicrobial agents in different composite films, against different bacteria.

5.1.1. Inorganic particles

Some examples of inorganic antimicrobial particles include nanoparticles of Cu, Ag, Ti, Zn, etc. Among these, AgNPs are known to show higher antimicrobial behavior compared to others and provide durable and strong antimicrobial activity. It has better bactericide properties against a vast range of bacteria, viruses and fungi.(Carbone, Donia, Sabbatella, & Antiochia, 2016; Chernousova & Epple, 2013) The chemical and physical characteristics of NC are of significant importance here. The composites prepared from CNF/AgNPs have numerous applications in the food industry as components of an active packaging system.(Zhang, Yu, Wang, & Yao, 2017) The mechanism of antimicrobial action of AgNPs and the role of NC in it have been studied by a number of researchers.(Aderibigbe, 2017; Dakal, Kumar, Majumdar, & Yadav, 2016; Guo, Yuan, Lu, & Li, 2013; Prabhu & Poulose, 2012; Su, Lin, Chen, Wu, & Wang, 2017) In a study, composite films constituting PVA, NC and AgNPs were fabricated and its effect on the thermo-mechanical properties of composite films of PVA were investigated.(Sarwar, Niazi, Jahan, Ahmad, & Hussain, 2018) Increase in tensile strength of PVA was observed and the film was successful in inhibiting bacterial activity against *Staphylococcus aureus* (*S. aureas*) and *Escherichia coli* (*E. coli*), stronger against the latter. With 16 wt.% NC at 0.3 g AgNPs, 12 wt.% NC at 0.5 g AgNPs, the inhibition zones for *S. aureas* and *E. coli* were up to 13.6 ± 0.68 mm and 14 ± 0.70 mm, respectively. The films formed possessed high moisture retaining capability which is suitable for storing fresh fruits and vegetables. The reason being, both PVA and NC are hydrophilic in nature, and help in moisture retention. The authors also placed their concern on the liberation of AgNPs and safety aspects to be considered before their direct use in packaging. In general, any material containing Ag, release Ag in the form of NPs or ions, prohibition of which is an important concern (Drake & Hazelwood, 2005).

The active functions of a packaging material can be enhanced using AgNPs because of their antimicrobial nature, but these nanomaterials pose toxic effects. Zhilong et al. investigated the cytotoxicity and antimicrobial effect of CNF/AgNPs nanocomposite on human colon cells (Zhilong, Wang, Kong, Lin, & Mustapha, 2019). The inhibitory effect of the composite was observed on the growth of *L. monocytogenes* and *E. Coli*, the effect being greater on the latter. There was no relevant sign of decrease in cell viability of human colon cells, tested at different concentrations of the composite (5–1000 u g/mL), proving the composite as non-toxic for at least 24 h. Addition of CNFs in a biopolymer can display improved water and oxygen impermeability and UV barrier capacity along with an extended shelf life for fresh sirloin beef (Zhilong et al., 2017).

Functionalization of NC imparts additional properties to the resultant material. TEMPO oxidized NC bonded with carboxylate groups, which can strongly bond with AgNPs further, is one such example. AgNPs also do not allow CNFs to coalesce as carboxylate-AgNP bonding limits the hydrogen bonding of adjacent CNFs (Dong, Snyder, Tran, & Leadore, 2013). CNFs were functionalized with AgNPs by means of Tollen's reaction by Amira et al. (Errokh, Magnin, Putaux, & Boufi, 2019). Mechanical properties of the nanocomposite film containing this functionalized nanofiller with acrylic matrix was hardly affected due to the presence of AgNPs. As AgNPs were bound on the CNF surface (confirmed with TEM), the amount it leached out of the film was much below the permissible limit of 12 ppb. This composite demonstrated good antibacterial properties and proved its potential in active packaging, adhesives and coatings as well (Lokanathan, Uddin, Rojas, & Laine, 2014; Wu et al., 2014).

El-Wakil et al. successfully prepared an active nanocomposite made of wheat gluten, TiO_2 nanoparticles and CNCs that exhibited antimicrobial activity against microorganisms such as *Saccharomyces cerevisiae*, *S. aureus* and *E. coli* (El-Wakil, Hassan, Abou-Zeid, & Dufresne, 2015).

BNC is prioritized over other NCs for biomedical and packaging applications in particular because of its purity. Although, the high production cost and process optimization to widen its effective application in food packaging sector of the same has limited its research (Azeredo, Barud, Farinas, Vasconcellos, & Claro, 2019; Portela da Gama & Dourado, 2018). Films made of BNC pose great thermal stability (~ 280 °C), transparency, high tensile strength, mechanical flexibility, light weight along with commendable capacity of liquid absorption and biocompatibility (Zeng, Laromaine, Feng, Levkin, & Roig, 2014). Panaitescu et al. proposed a green solution for packaging, which was a composite produced by modifying PHB with BNC via melt processing, followed by plasma treatment or ZnO nanoparticle plasma coating (Panaitescu et al., 2018). The plasma treatment reduced the bacterial growth by 40–60 %. Irrespective of the BNC concentration, it also preserved the crystallinity, melt behavior and thermal stability of the composite. On the other hand, ZnO nanoparticle plasma coating completely limited the growth of *S. aureus* along with improved mechanical, thermal behaviour and morphology of PHB-BNC, attributed to strong chemical bond between PHB and metal oxide nanoparticles.

BNC/PVA/AgNP films were produced by Wang et al. using UV-assisted method (UV) and reduction method (R) (Wang et al., 2019). Fig. 8(a) shows that, at any point of time, more number of AgNPs were released in UV film (than R film), but at a slower rate. Over a span of 24 h the bacterial concentration inside the UV film reduced dramatically, by 7.3 log CFU/mL, and by 4.8 log CFU/mL in R film. Attributed to more effective control of bacterial growth, the UV film can be useful in prolonging the shelf-life of the stored beef. They conducted another experiment to check the longevity of the effect of various films on the growth of natural bacteria on beef (See Fig. 8(b)). It was concluded that the presence of AgNPs can effectively inhibit the growth of bacteria for 10 days at 4 °C and the inhibition effect is more prominent in the beef wrapped with UV film.

5.1.2. Organic particles

Nisin (Salmieri et al., 2014), and some essential oils (EO) such as clove EO (Adel, Ibrahim, El-Shafei, & Al-Shemy, 2019), have been used as organic antimicrobial additives in composite films. These organic materials hinder the vital metabolism of the pathogens while some even disrupt their cell wall and functions (Dhifi, Bellili, Jazi, Bahloul, & Mnif, 2016). Each of these materials help in inhibiting the growth of specific pathogens. For instance, Lignin nanoparticle incorporated PLA-CNC film inhibits *Pseudomonas syringae* (Yang et al., 2016), nisin completely inhibits *L. monocytogenes* (Salmieri et al., 2014), etc. Plant-derived EOs on the other hand, display good antifungal, antibacterial, antioxidant and antiviral characteristics (Bakkali, Averbeck, Averbeck, & Idaomar, 2008). A composite was prepared from chitosan/β-cyclodextrin citrate and oxidized NC. Clove EO was added to the composite and restraint was observed against gram-negative bacteria, gram-positive bacteria, yeast and fungus (Adel et al., 2019). Abdollahi et al. developed CMC-agar biocomposite employing solvent casting method and varied the concentration (0.5, 1, 1.5 % v/v) of summer savory essential oil (SSEO) in it (Abdollahi, Damirchi, Shafafi, Rezaei, & Ariaii, 2019). They observed that the film acted powerfully active against Gram-positive bacteria and were less powerful against Gram-negative bacteria. It was also found that the higher concentration of SSEO (≥ 1 %) in the film increased water vapor permeability (due to microstructural heterogeneity) and reduced the tensile strength; both approximately by 25 %. Nisin is another material having similar properties with respect to controlled release by nanocomposite material as that of EOs. Nisin (0.25-0.5 wt.%) was incorporated into CNC/corn distarch phosphate based bio-film along with ε-polylysine (PL) (0.2 wt.%) by Sun et al. (Sun et al., 2019). The film showed antimicrobial activity against *S. aureas* and

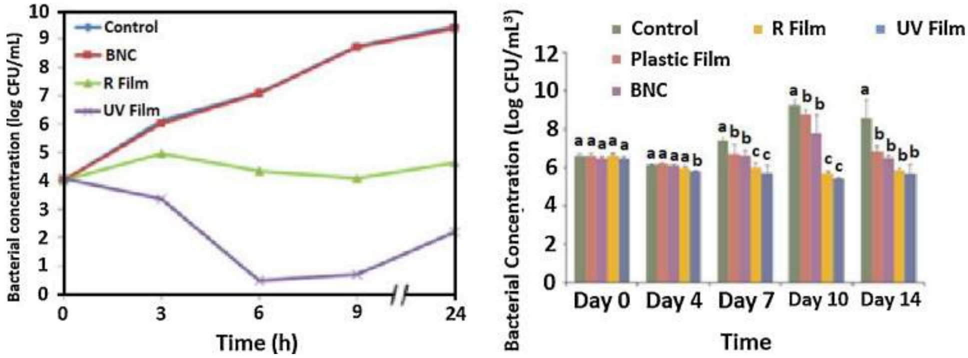

Fig. 8. (a) Bacterial concentration with time in different films; (b) Comparison of bacterial concentration in different films, with UV films being the most effective. (Wang et al., 2019).

E. coli, attributed to the combination of PL and nisin. The synergistic effect of nisin and PL in expanding the inhibitory zone can be clearly seen in Fig. 9. Bagde et al. demonstrated that Bacteriocin Immobilized CNC (BIC) is a potential antimicrobial additive (57 % reduction in bacterial count) in a corn starch film (Bagde & Nadanathangam, 2019). It was observed that the incorporation of BIC also improved tensile strength (69 %) and reduced optical transparency (~28 %).

Recently, to replace AgNPs from packaging ingredients, Maliha et al. incorporated organobismuth complex (phenyl bismuth bis(diphenylphosphinato)) into NC sheets employing spray technique. The as-formed nanocomposite films were successful in inhibiting the growth of fungi and medically important multi drug restraint bacteria at higher loading of bismuth complex (>1.5 wt%) (Maliha et al., 2020) (Table 2). Zhilong et al. prepared an active biodegradable film by adding pine needle extract (PNE), lactic acid and CNF into soy protein films. Successful antimicrobial activity against foodborne pathogens (*E-coli, L. monocytogenes*, *S. aureas* and *Salmonella typhimurium*) along with antioxidant and light barrier properties were observed. CNF was responsible for enhancing the tensile strength and controlled release of lactic acid and PNE from the matrix that ameliorated antioxidant and antimicrobial properties (Zhilong, Dhital et al., 2019).

NC derived from natural fibers act as bioactive material as well. Fibers obtained from ginger also have bioactive chemicals in it which hinder the growth of microorganisms, showing good antimicrobial activity (Jacob, Haponiuk, Thomas, Peter, & Gopi, 2018; Zick et al., 2008). Abral et al. investigated the antimicrobial properties of cellulose film processed from ginger nanofibers (Abral et al., 2019). The processing involved chemical treatment along with ultrasonication. The film was able to transmit 83 % of the light at 650 nm, making it more transparent and also demonstrated good antimicrobial properties. A superabsorbent bioactive aerogel was produced using A. donax derived cellulosic fractions and bioactive extracts via freeze-drying method (Fontes-Candia, Erboz, Martínez-Abad, López-Rubio, & Martínez-Sanz, 2019).

The antioxidant properties of the as prepared composite were testified as absorbent pads on red meat. The aqueous extract from A. donax was found to have high antioxidant capacity. The color loss and lipid oxidation of the red meat was successfully reduced.

5.2. Responsive packaging (RP)

In simple words, responsive packaging can be termed as packaging containing an indicator which provides information on food quality and microbial activity (Lim, 2011). This can be achieved by use of different biosensors, gas indicators, time temperature indicators and barcode labels which record any internal or external changes in the surroundings of the product (de Jong et al., 2005; Poyatos-Racionero, Ros-Lis, Vivancos, & Martínez-Máñez, 2018). Responsive packaging is often termed as smart packaging, intelligent packaging or biosensing.

Recently, Vilela et al. fabricated a bottom-up built (*in-situ* polymerization) composite film composed of poly(sulfobetaine methacrylate) (PSBMA), a zwitterionic polymer showing polyelectrolyte and anti-polyelectrolyte behavior (Blackman, Gunatillake, Cass, & Locock, 2019; Yang, Zhang, Tarabara, & Bruening, 2018), within the nanofibrous structure of BNC (Vilela et al., 2019). The study was aimed at making a packaging film which could be used to monitor the humidity levels of moisture intolerant food products (meat products, dry foods or dairy products). The proton conductivity of the composite varied from 1.5×10^{-4} mS cm^{-1} (at 60 % RH, 40 °C) to 1.5 mS cm^{-1} (at 98 % RH, 94

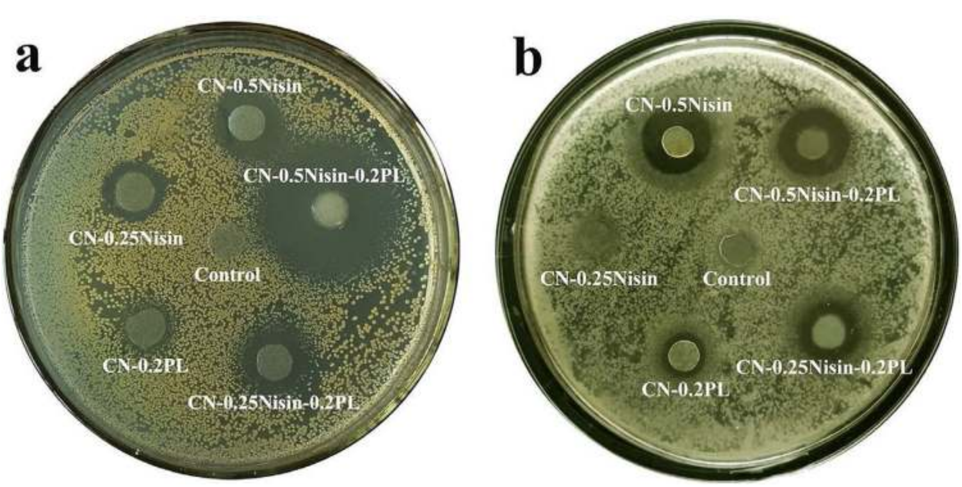

Fig. 9. Inhibition zones of films incorporated with different contents of nisin and PL(Sun et al., 2019).

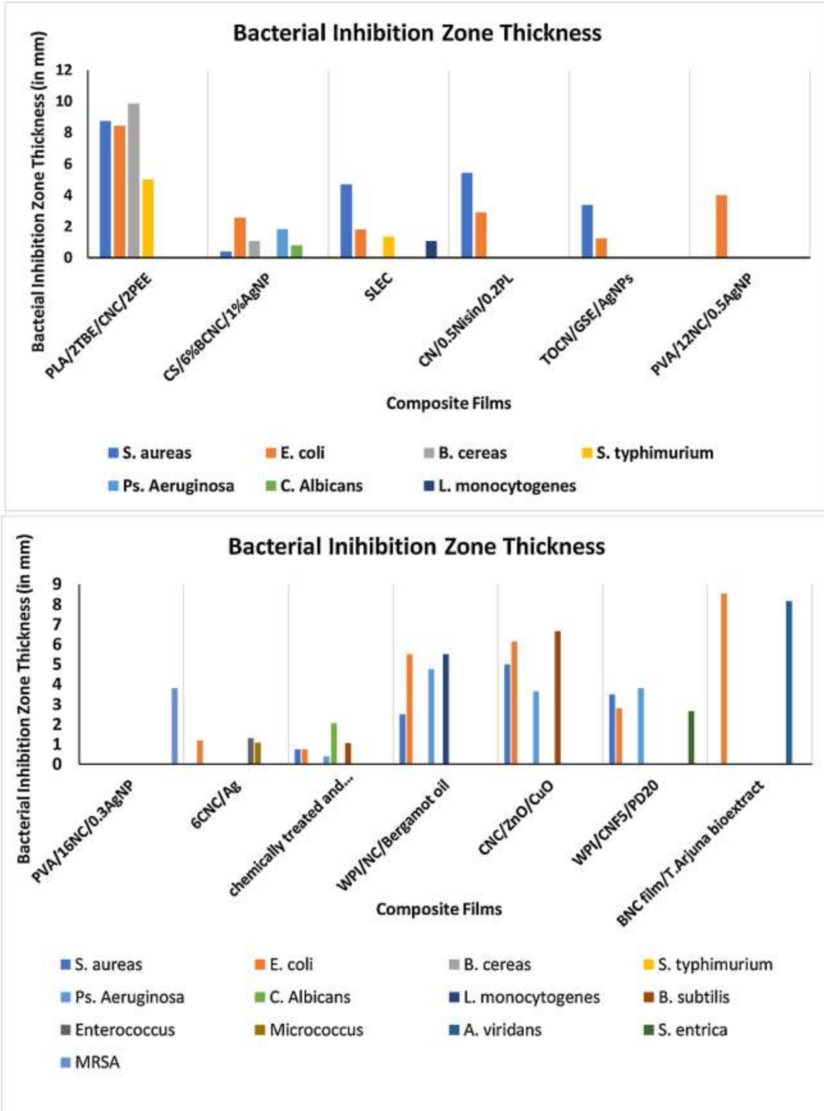

Fig. 10. Bacterial Inhibition zone thickness of different compositions – PLA/2TBE/CNC/2PEE,(Khodayari et al., 2019) CS/6 %BCNC/1 %AgNP,(Salari, Sowti Khiabani, Rezaei Mokarram, Ghanbarzadeh, & Samadi Kafil, 2018) SLEC, (Zhilong, Dhital et al., 2019) CNC/0.5Nisin/2 PL,(Sun et al., 2019) TOCN/GSE/AgNPs,(Wu et al., 2019) PVA/12NC/0.5AgNP, (Sarwar et al., 2018) PVA/16NC/0.3AgNP,(Sarwar et al., 2018) 6CNC/Ag,(Errokh et al., 2019) Chemically treated and ultrasonicated Ginger fibres,(Abral et al., 2019) WPI/NC/Bergamot oil,(Sogut, 2020) CNC/ZnO/CuO,(Elfeky et al., 2020) WPI/CNF5/PD20,(Karimi, Alizadeh, Almasi, & Hanifian, 2020) BNC film/T. arjuna bioextract.(C. Sharma & Bhardwaj, 2019).

°C). The composite film prepared possessed protonic conductivity, a major asset for intelligent packaging, helping in protonic-conduction humidity sensing (Farahani, Wagiran, & Hamidon, 2014). Additionally, increased water-uptake capacity (450–559 %), high thermal stability (up to 265 °C) (placed in nitrogen environment), improved mechanical properties (Young's Modulus $\geq$ 3.1 GPa), barrier against UV radiations were also observed. This composite film was successful in inhibiting *S. aureas* and *E. coli* bacteria as well. Sobhan et al. integrated the concept of biosensing to the smart packaging application by developing a functional NC and activated carbon (NAC) film, which combined the electrochemical properties of activated carbon (AC) with the thermo-mechanical properties of functionalized NC (Sobhan, Muthukumarappan, Cen, & Wei, 2019).

The quality of the food, which is affected by the chemical and microbial activities, can be monitored on a real-time basis with the help of freshness indicators. Visual observations (change in color of the indicators), resulting from the reactions between metabolites and indicators, form the basis for determining the freshness of the food (Biji, Ravishankar, Mohan, & Srinivasa Gopal, 2015). Changes in milk can be expressed via pH and acidity and thus the real-time monitoring of its quality is possible using suitable indicators. A smart pH monitoring label was developed by doping BNC with red cabbage anthocyanin extracts (32 and 193 mg L^{-1}) (Pourjavaher, Almasi, Meshkini, Pirsa, & Parandi, 2017). The indicator, containing diluted anthocyanins was responsive to pH 2–10 with distinguishable color change at different pH values (see Fig. 11). The moisture absorbency of a pH indicator film directly affects the color response efficiency of the film. On addition of diluted red cabbage anthocyanin extract, nearly 15 % increase in moisture absorbency and 69 % increment on the addition of concentrated anthocyanin extract. However, the mechanical properties (Modulus and Ultimate tensile strength) of the former were better compared to the latter.

6. Mechanical properties

An essential requirement for good food packaging material is to have sound mechanical properties. Biopolymers have poor mechanical properties. Crosslinking or grafting of monomers has been assessed to improve the required properties (Criado, Hossain, Salmieri, & Lacroix, 2017). The presence of NC in the biopolymer increases the strength and modulus of the resultant nanocomposite.(Fortunati, Kenny, & Torre, 2019) These properties enhance with increasing concentration of NC in the matrix, up to a particular limit (approximately 4 %) (Abdallah, Mirzadeh, Tan, & Kamal, 2019; Fang, Chen, Wang, Cheng, & Ding, 2019). At this concentration, NC forms its continuous 3D network in the matrix. Above this value, the NC segregates in the matrix due to hydrogen bonding between OH groups, impairing the properties of the

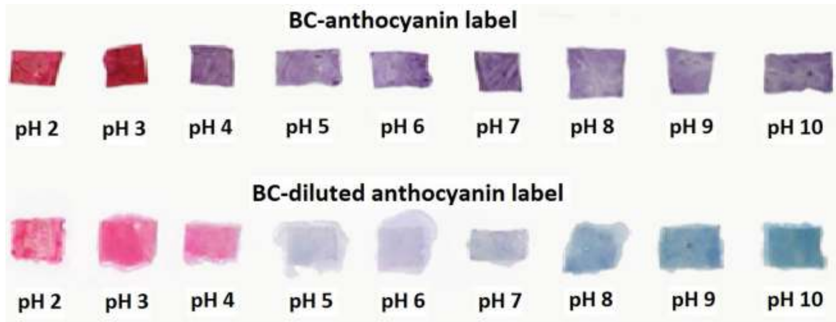

Fig. 11. Color response of BC/anthocyanin and BC/diluted-anthocyanin pH indicator at pH 2–10 (Pourjavaher et al., 2017).

composites. Segregation of NC also reduces the water vapor barrier and optical (transparency) properties. Santos et al. observed that the ultra-sonication favors NC dispersion and hence the aforementioned property enhancements (Santos et al., 2014). The biodegradable film comprising incorporation of sugar palm CNF in sugar palm starch (SPS), both considered to be agricultural residues, displayed the strength and modulus enhancement by more than 100 % at just 1 % CNF (Ilyas et al., 2019). Mechanical characterization was done on starch based composite films containing varied concentrations of bamboo derived NC, cotton linter derived NC and sisal derived NC (Chen et al., 2019). Tensile strength was greatly increased with NC addition at first but it was weakened or remained constant on further addition of NC. This was observed because large amount of NC led to its reduced interaction with polymer matrix. Elongation at break gradually decreases with increase in NC content because of rigid network formed by NC restricts the flow of starch molecular chain. B-NC was found out to impart highest reinforcing strength required for the films as it has the largest aspect ratio. In general, CNC offers better elongation properties compared to CNF and BNC as the later are subjected to entanglements due to higher aspect ratio and consequently causing agglomeration.

The mechanical properties of BNC reinforced polymer nanocomposites depend mainly on the processing method followed. Bottom-up built nanocomposites (*in-situ* process) is a process wherein, the growth of BC nanofibrils takes place (in a culture medium) in presence of second biopolymer. The same nanocomposite can also be manufactured employing impregnation of BNC into the biopolymer matrix. The earlier process has an advantage of much higher strength and modulus due to a coherent network formation and intact nanofibril arrangement (Gea, Bilotti, Reynolds, Soykeabkeaw, & Peijs, 2010). The drop in the strength and modulus in impregnation process is attributed to aggregate formation of BNC. The disadvantage with the bottom-up approach lies in not allowing to make changes in shape after fermentation.

In a case, wherein, paperboard was coated with TOCN and PPy, it was observed that the tensile strength and young's modulus increased by 2.5 and 3 times, respectively, presence of TOCN chains were mainly responsible for enhanced strength (Bideau et al., 2018). However the elongation at break(%) decreased with a great value because of presence of PPy. Sobhan et al. prepared a film from NAC for smart packaging and observed enhanced mechanical properties (Fig. 12). High tensile strength is desired as it proves to be useful in food shipping, transportation and handling by resisting the encountered stress (Sobhan et al., 2019).

Apart from imparting antibacterial properties to the composite, George et al. observed that the AgNPs aid CNCs in increasing the tensile strength, modulus, ductility and moisture barrier of the Hydroxypropyl Methylcellulose (HPMC) matrix (George et al., 2014). FTIR study displayed the physical crosslinking due to the interactions of AgNPs with OH groups of HPMC. Sarwar et al. employed casting method to develop NC/Ag/PVA nanocomposite film and investigated the effect of NC and AgNPs on its various properties (Sarwar et al., 2018). For 8 wt% of NC into PVA, mechanical strength of the film was increased by 123 % to 12.3 MPa compared with PVA matrix. Incorporation of only 1 wt% AgNPs to this composition, not only the strength of the film enhanced by 580 % to 83.4 MPa, but also manifested non-cytotoxicity effect along with strong antimicrobial properties against both Gram-positive and Gram-negative bacteria. The increase in strength was attributed to the physical interaction between PVA and AgNPs (Table 3).

7. Thermal properties

The thermal stability of a film decreases with increase in the concentration of CNC. The thermal degradation of film occurs in the following steps – (i) liberation of moisture; (ii) degradation of constituents, resulting in the weight loss of the film. For instance, Cao et al. observed weight loss of the carboxylated CNC whiskers reinforced cassia gum matrix in the temperature range of 20–106 °C and 204–317 °C

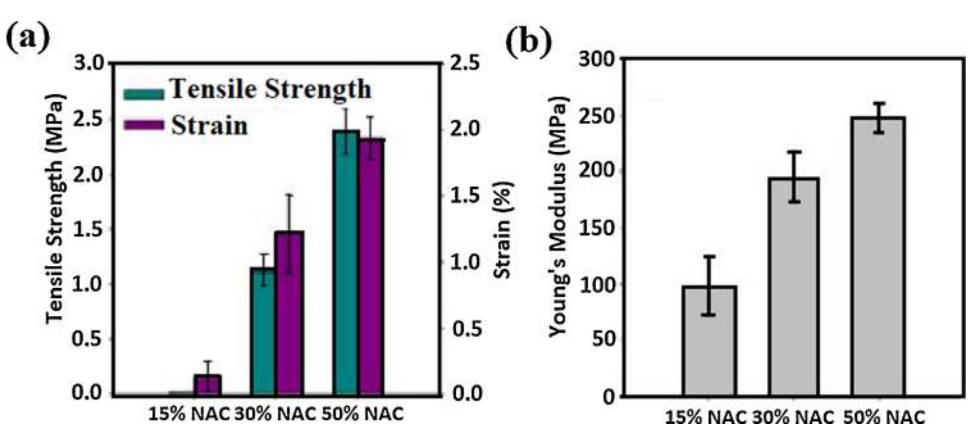

Fig. 12. Mechanical properties of 15 %, 30 % and 50 % NAC films. (A) Tensile strength (TS) and strain of NAC films; (B) Young modulus of NAC films (Sobhan et al., 2019).

Table 3
Mechanical properties of recently prepared packaging films.

CNC source	Polymer Matrix	Preparation Procedure	Filler content (wt%)	σ* (MPa)	E* (GPa)	ε* (%)	Ref
University of Maine, USA	PBS	*In-situ* polymerization	0.5	42.1 > 54.3	0.69 > 0.83	230 > 357	(Kim et al., 2018)
MCC	PBAT	Melt mixing	7	22.0 < 12.4	0.05 > 0.08	544.5 < 567.4	(Pinheiro et al., 2017)
MCC	PBAT	Casting	10	6.3 > 7.2	0.06 > 0.12	10.2 < 5.8	(Morelli, Belgacem, Branciforti et al., 2016)
MCC	PBAT	Melt mixing	10	5.8 = 5.8	0.06 > 0.08	30 < 20	(Morelli, Belgacem, Bretas, & Bras, 2016)
MCC	PBAT	Melt mixing	0.5	11.0 < 9.7	0.04 > 0.12	927 < 558	(Zhang, Ma, & Y. Z., 2016)
MCC	PLA	Casting	5	55 < 54	1.3 > 1.6	9 < 7	(Gårdebjer et al., 2015)
MCC	PHB	Casting	5	25 < 23	1.4 > 1.8	4 < 3	(Gårdebjer et al., 2015)
MCC	PLA	Casting	2.5	40 > 51	–	4.3 > 5.6	(Espino-Pérez et al., 2013)
MCC	PLA	Melt mixing	5	43 > 46	2400 > 4400	90 < 18	(Fortunati, Armentano et al., 2012)
Cotton	PLLA	Casting	2	48.3 > 58.6	1.1 > 1.4	31.1 < 8.3	(Pei, Zhou, & Berglund, 2010)
	PHB/PCL		3	14.7 < 14.5	949 < 902	3.9 > 4.1	(Garcia-Garcia et al., 2018)
	PHB/PCL		5	14.7 < 9.3	949 > 1006	3.9 < 1.8	(Garcia-Garcia et al., 2018)
	PHB/PCL		7	14.7 < 6.5	949 > 972	3.9 < 0.4	(Garcia-Garcia et al., 2018)
	TOCN Paperboard/TOCN coated Paperboard			15.16 > 36.80	0.93 > 2.92	7.66 < 2.36	(Bideau et al., 2018)

σ - strength; E - modulus of elasticity; ε- elongation at break. The properties were compared between CNC-based nanocomposites and neat polymer. * > improved and < decreased properties.

respectively.(Cao et al., 2020) The factors leading to these weight losses were evaporation of water for the first, and pyrolysis of cellulose for the second.(Peng, Zhang, & Zhang, 2019) In case of films made of PHB_{75}/PCL_{25}, when increasing loads of CNCs were added to these films, thermal stability was decreasing. (Daniel Garcia-Garcia, Lopez-Martinez, Balart, Strömberg, & Moriana, 2018) (D. Garcia-Garcia, Rayón, Carbonell-Verdu, Lopez-Martinez, & Balart, 2017)

Panaitescu et al. did NC and plasma treatment on PHB and found preservation of thermal stability through TGA.(Panaitescu et al., 2018) The overall thermal stability gets influenced by plasma treatment and T_{max} was found to be increased by 1.5–4.4 °C when BNC was 1−2 wt%. However, a decrease of 5.2 % in temperature was observed at 5 wt.% of BNC, demonstrating plasma sensitivity for cellulose. (Vizireanu et al., 2018) Thermal degradation of chitin-cellulose nanocomposite was also observed by the use of TGA. The thermal stability of chitin nanofiber (CTNF) was found to be better than bamboo cellulose nanofiber (BACNF).(Hai, Choi, Zhai, Panicker, & Kim, 2020) Also with less percentage of reinforcement of BACNF thermal stability of CTNF-BACNF has very little change, although when the concentration of BACNF was increased to 25 % and 40 % then the thermal stability was found to be in between BACNF and CTNF. This gives prove that CTNF help in the thermal stability of BACNF (Hai et al., 2020).

Extraction for cellulose, can be carried via formic acid hydrolysis, TEMPO-mediated oxidation, pulp-refining and sulfuric acid hydrolysis. The CNC formed from formic acid hydrolysis has been observed to show better thermal stability and aspect ratio (Liu et al., 2016). Enzyme processed Bacterial Cellulose is more thermally stable (stable upto 378 °C) than the acid hydrolyzed one (George & Siddaramaiah, 2012).

8. Conclusion and inference

NC obtained from renewable resources, is biodegradable, voluminously available and sustainable, reprocessible and recyclable packaging material. However, using NC alone is not desired, as it offers poor resistance to water vapor hence is not suitable for use at high humidity levels. The presence of NC in the film as a filler or coating not only enhances the barrier properties, including gases and water vapor, but also imparts requisite mechanical properties to it. It was also observed that the elongation at break and the thermal stability of the composite film decreased with increasing concentration of NC. The chemical surface modification of cellulose, in a way that it doesn't affect the inherent properties of same, is required.

The production of greener food packaging materials and understanding of how various antimicrobial agents behave in presence of NC when present in the packaging film has laid the foundation of new concepts in antimicrobial packaging, offering innumerable advantages in the field of AP. There is a need to identify new active agents that are responsive against a wide variety of microorganisms in AP systems. Also, focus on migration behavior of such antimicrobial agents is required as its higher amount in food is very limited as per standards (For example, upper limit for AgNPs is 0.05 mg/kg of food as per European Food Safety Authority)

In the last couple of years, researchers have attempted manufacturing of active biodegradable films employing completely green routes which does not require usage of any chemical reducing agent in the processes like plant extract reduction, UV reduction methods. BNC has interesting applications in food packaging, but not being explored much as its high production cost is a big hurdle and its commercialization for packaging market is still a challenge.

Though significant advances have been made, an equilibrium between the environmental concern, cost considerations, performance during use and the shelf-life of the film is yet far from achieving. Even though with the recent approaches of making controlled release of antimicrobial agents in presence of NC possible; using bio-polymers as raw materials having desired barrier properties, tensile strength and meeting the food packaging requirements is still a big challenge to overcome. To exploit NC in commercial packaging, material scientists, and engineers should work hand-in-hand. The prevalent employment of such a biodegradable and sustainable NC replacing its plastic counterpart will surely contribute in reduction of the greenhouse gases.

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030-01).

References

Abdallah, W., Mirzadeh, A., Tan, V., & Kamal, M. R. (2019). Influence of nanoparticle pretreatment on the thermal, rheological and mechanical properties of PLA-PBSA nanocomposites incorporating cellulose nanocrystals or montmorillonite. *Nanomaterials, 9*(1), 29. https://doi.org/10.3390/nano9010029

Abdollahi, M., Damirchi, S., Shafafi, M., Rezaei, M., & Ariaii, P. (2019). Carboxymethyl cellulose-agar biocomposite film activated with summer savory essential oil as an antimicrobial agent. *International Journal of Biological Macromolecules, 126*, 561–568. https://doi.org/10.1016/j.ijbiomac.2018.12.115

Abdul Khalil, H. P. S., Davoudpour, Y., Saurabh, C. K., Hossain, M. S., Adnan, A. S., Dungani, R., et al. (2016). A review on nanocellulosic fibres as new material for sustainable packaging: Process and applications. *Renewable and Sustainable Energy Reviews, 64*, 823–836. https://doi.org/10.1016/J.RSER.2016.06.072

Abral, H., Ariksa, J., Mahardika, M., Handayani, D., Aminah, I., Sandrawati, N., et al. (2019). Transparent and antimicrobial cellulose film from ginger nanofiber Food Hydrocolloids Transparent and antimicrobial cellulose fi lm from ginger nano fiber. *Food Hydrocolloids, 98*, 105266. https://doi.org/10.1016/j.foodhyd.2019.105266

Adel, A. M., Ibrahim, A. A., El-Shafei, A. M., & Al-Shemy, M. T. (2019). Inclusion complex of clove oil with chitosan/β-cyclodextrin citrate/oxidized nanocellulose biocomposite for active food packaging. *Food Packaging and Shelf Life, 20*, 100307. https://doi.org/10.1016/j.fpsl.2019.100307

Aderibigbe, B. A. (2017). Metal-based nanoparticles for the treatment of infectious diseases. *Molecules, 22*(8). https://doi.org/10.3390/molecules22081370

Ahmed, J., & Varshney, S. K. (2011). Polylactides-chemistry, properties and green packaging technology: A review. *International Journal of Food Properties, 14*(1), 37–58. https://doi.org/10.1080/10942910903125284

Appendini, P., & Hotchkiss, J. H. (2002). Review of antimicrobial food packaging. *Innovative Food Science & Emerging Technologies, 3*(2), 113–126.

Aulin, C., Gällstedt, M., & Lindström, T. (2010). Oxygen and oil barrier properties of microfibrillated cellulose films and coatings. *Cellulose, 17*(3), 559–574.

Azeredo, H. M. C., Barud, H., Farinas, C. S., Vasconcellos, V. M., & Claro, A. M. (2019). Bacterial cellulose as a raw material for food and food packaging applications. *Frontiers in Sustainable Food Systems, 3*, 00007. https://doi.org/10.3389/fsufs.2019.00007

Azeredo, H. M. C., Miranda, K. W. E., Ribeiro, H. L., Rosa, M. F., & Nascimento, D. M. (2012). Nanoreinforced alginate-acerola puree coatings on acerola fruits. *Journal of Food Engineering, 113*(4), 505–510. https://doi.org/10.1016/j.jfoodeng.2012.08.006

Azeredo, H. M. C., Rosa, M. F., & Mattoso, L. H. C. (2017). Nanocellulose in bio-based food packaging applications. *Industrial Crops and Products, 97*, 664–671. https://doi.org/10.1016/J.INDCROP.2016.03.013

Azizi, S., & Mohamad, R. (2018). Mechanical and barrier properties of kappa-carrageenan/cellulose nanocrystals bio-nanocomposite films. *IOP Conference Series: Materials Science and Engineering, 368*. https://doi.org/10.1088/1757-899X/368/1/012013, 1.

Bagde, P., & Nadanathangam, V. (2019). Mechanical, antibacterial and biodegradable properties of starch film containing bacteriocin immobilized crystalline nanocellulose. *Carbohydrate Polymers, 222*, 115021. https://doi.org/10.1016/j.carbpol.2019.115021

Bakkali, F., Averbeck, S., Averbeck, D., & Idaomar, M. (2008). Biological effects of essential oils - A review. *Food and Chemical Toxicology, 46*(2), 446–475. https://doi.org/10.1016/j.fct.2007.09.106

Bao, Y., Zhang, H., Luan, Q., Zheng, M., Tang, H., & Huang, F. (2018). Fabrication of cellulose nanowhiskers reinforced chitosan-xylan nanocomposite films with antibacterial and antioxidant activities. *Carbohydrate Polymers, 184*, 66–73. https://doi.org/10.1016/j.carbpol.2017.12.051

Bardet, R., Reverdy, C., Belgacem, N., Leirset, I., Syverud, K., Bardet, M., et al. (2015). Substitution of nanoclay in high gas barrier films of cellulose nanofibrils with cellulose nanocrystals and thermal treatment. *Cellulose, 22*(2), 1227–1241. https://doi.org/10.1007/s10570-015-0547-9

Basu, S., Plucinski, A., & Catchmark, J. M. (2017). Sustainable barrier materials based on polysaccharide polyelectrolyte complexes. *Green Chemistry, 19*(17), 4080–4092. https://doi.org/10.1039/c7gc00991g

Belbekhouche, S., Bras, J., Siqueira, G., Chappey, C., Lebrun, L., Khelifi, B., et al. (2011). Water sorption behavior and gas barrier properties of cellulose whiskers and microfibrils films. *Carbohydrate Polymers, 83*(4), 1740–1748. https://doi.org/10.1016/j.carbpol.2010.10.036

Benito-Peña, E., González-Vallejo, V., Rico-Yuste, A., Barbosa-Pereira, L., Cruz, J. M., Bilbao, A., et al. (2016). Molecularly imprinted hydrogels as functional active packaging materials. *Food Chemistry, 190*, 487–494. https://doi.org/10.1016/J.FOODCHEM.2015.05.128

Benyoussif, Y., Aboulhrouz, S., El Achaby, M., Cherkaoui, O., Lallam, A., El Bouchti, M., et al. (2015). Preparation and properties of bionanocomposite films reinforced with Nanocellulose isolated from Moroccan Alfa Fibres. *AUTEX Research Journal, 15*(3), 164–172. https://doi.org/10.1515/aut-2015-0011

Berthet, M. A., Angellier-Coussy, H., Guillard, V., & Gontard, N. (2016). Vegetal fiber-based biocomposites: Which stakes for food packaging applications? *Journal of Applied Polymer Science, 133*(2), 42528. https://doi.org/10.1002/app.42528

Bideau, B., Bras, J., Adoui, N., Loranger, E., & Daneault, C. (2017). Polypyrrole/nanocellulose composite for food preservation: Barrier and antioxidant characterization. *Food Packaging and Shelf Life, 12*, 1–8. https://doi.org/10.1016/j.fpsl.2017.01.007

Bideau, B., Bras, J., Saini, S., Daneault, C., & Loranger, E. (2016). Mechanical and antibacterial properties of a nanocellulose-polypyrrole multilayer composite. *Materials Science and Engineering C, 69*, 977–984. https://doi.org/10.1016/j.msec.2016.08.005

Bideau, B., Loranger, E., & Daneault, C. (2018). Nanocellulose-polypyrrole-coated paperboard for food packaging application. *Progress in Organic Coatings, 123*, 128–133. https://doi.org/10.1016/j.porgcoat.2018.07.003

Biedermann-Brem, S., Biedermann, M., & Grob, K. (2016). Required barrier efficiency of internal bags against the migration from recycled paperboard packaging into food: A benchmark. *Food Additives & Contaminants: Part A, 33*(4), 1–16. https://doi.org/10.1080/19440049.2016.1160744

Biji, K. B., Ravishankar, C. N., Mohan, C. O., & Srinivasa Gopal, T. K. (2015). Smart packaging systems for food applications: A review. *Journal of Food Science and Technology, 52*(10), 6125–6135. https://doi.org/10.1007/s13197-015-1766-7

Blackman, L. D., Gunatillake, P. A., Cass, P., & Locock, K. E. S. (2019). An introduction to zwitterionic polymer behavior and applications in solution and at surfaces. *Chemical Society Reviews, 48*(3), 757–770. https://doi.org/10.1039/c8cs00508g

Bonilla, J., Atarés, L., Vargas, M., & Chiralt, A. (2013). Properties of wheat starch film-forming dispersions and films as affected by chitosan addition. *Journal of Food Engineering, 114*(3), 303–312. https://doi.org/10.1016/J.JFOODENG.2012.08.005

Boufi, S., González, I., Delgado-Aguilar, M., Tarrès, Q., Pèlach, M.À., & Mutjé, P. (2016). Nanofibrillated cellulose as an additive in papermaking process: A review. *Carbohydrate Polymers, 154*, 151–166. https://doi.org/10.1016/J.CARBPOL.2016.07.117

Brockgreitens, J., & Abbas, A. (2016). Responsive food packaging: Recent progress and technological prospects. *Comprehensive Reviews in Food Science and Food Safety, 15*(1), 3–15. https://doi.org/10.1111/1541-4337.12174

Burgos, N., Tolaguera, D., Fiori, S., & Jiménez, A. (2014). Synthesis and characterization of lactic acid oligomers: Evaluation of performance as poly(Lactic acid) plasticizers. *Journal of Polymers and the Environment, 22*(2), 227–235. https://doi.org/10.1007/s10924-013-0628-5

Byun, Y., Kim, Y. T., & Whiteside, S. (2010). Characterization of an antioxidant polylactic acid (PLA) film prepared with α-tocopherol, BHT and polyethylene glycol using film cast extruder. *Journal of Food Engineering, 100*(2), 239–244. https://doi.org/10.1016/j.jfoodeng.2010.04.005

Cao, L., Ge, T., Meng, F., Xu, S., Li, J., & Wang, L. (2020). An edible oil packaging film with improved barrier properties and heat sealability from cassia gum incorporating carboxylated cellulose nano crystal whisker. *Food Hydrocolloids, 98*, 105251. https://doi.org/10.1016/j.foodhyd.2019.105251

Carbone, M., Donia, D. T., Sabbatella, G., & Antiochia, R. (2016). Silver nanoparticles in polymeric matrices for fresh food packaging. *Journal of King Saud University - Science, 28*(4), 273–279. https://doi.org/10.1016/j.jksus.2016.05.004

Cazón, P., Velazquez, G., & Vázquez, M. (2019). Novel composite films from regenerated cellulose-glycerol-polyvinyl alcohol: Mechanical and barrier properties. *Food Hydrocolloids, 89*, 481–491. https://doi.org/10.1016/j.foodhyd.2018.11.012

Cazón, P., Velazquez, G., & Vázquez, M. (2020). Characterization of mechanical and barrier properties of bacterial cellulose, glycerol and polyvinyl alcohol (PVOH) composite films with eco-friendly UV-protective properties. *Food Hydrocolloids, 99*, 105323. https://doi.org/10.1016/j.foodhyd.2019.105323

Cazón, P., Vázquez, M., & Velazquez, G. (2018a). Cellulose-glycerol-polyvinyl alcohol composite films for food packaging: Evaluation of water adsorption, mechanical properties, light-barrier properties and transparency. *Carbohydrate Polymers, 195*, 432–443. https://doi.org/10.1016/j.carbpol.2018.04.120

Cazón, P., Vázquez, M., & Velazquez, G. (2018b). Composite films of regenerate cellulose with chitosan and polyvinyl alcohol: Evaluation of water adsorption, mechanical and optical properties. *International Journal of Biological Macromolecules, 117*, 235–246. https://doi.org/10.1016/j.ijbiomac.2018.05.148

Chen, Q., Liu, Y., & Chen, G. (2019). A comparative study on the starch-based biocomposite films reinforced by nanocellulose prepared from different non-wood fibers. *Cellulose, 26*(4), 2425–2435. https://doi.org/10.1007/s10570-019-02254-x

Chernousova, S., & Epple, M. (2013). Silver as antibacterial agent: Ion, nanoparticle, and metal. *Angewandte Chemie - International Edition, 52*(6), 1636–1653. https://doi.org/10.1002/anie.201205923

Chi, K., & Catchmark, J. M. (2018). Improved eco-friendly barrier materials based on crystalline nanocellulose/chitosan/carboxymethyl cellulose polyelectrolyte complexes. *Food Hydrocolloids, 80*, 195–205. https://doi.org/10.1016/j.foodhyd.2018.02.003

Ching, Y. C., Rahman, A., Ching, K. Y., Sukiman, N. L., & Cheng, H. C. (2015). Preparation and characterization of polyvinyl alcohol-based composite reinforced with nanocellulose and nanosilica. *BioResources, 10*(2), 3364–3377. https://doi.org/10.15376/biores.10.2.3364-3377

Ciannamea, E. M., Castillo, L. A., Barbosa, S. E., & De Angelis, M. G. (2018). Barrier properties and mechanical strength of bio-renewable, heat-sealable films based on gelatin, glycerol and soybean oil for sustainable food packaging. *Reactive and Functional Polymers, 125*, 29–36. https://doi.org/10.1016/j.reactfunctpolym.2018.02.001

Cozzolino, C. A., Campanella, G., Türe, H., Olsson, R. T., & Farris, S. (2016). Microfibrillated cellulose and borax as mechanical, O2-barrier, and surface-modulating agents of pullulan biocomposite coatings on BOPP. *Carbohydrate Polymers, 143*, 179–187. https://doi.org/10.1016/j.carbpol.2016.01.068

Criado, P., Fraschini, C., Salmieri, S., Becher, D., Safrany, A., & Lacroix, M. (2014). Free radical grafting of gallic acid (GA) on cellulose nanocrystals (CNCS) and evaluation of antioxidant reinforced gellan gum films. *Radiation Physics and Chemistry, 118*, 61–69. https://doi.org/10.1016/j.radphyschem.2015.05.030

Criado, P., Hossain, F. M. J., Salmieri, S., & Lacroix, M. (2017). Nanocellulose in food packaging. *Composites Materials for Food Packaging*, 297–329. https://doi.org/10.1002/9781119160243. ch10.

Dai, L., Long, Z., Chen, J., An, X., Cheng, D., Khan, A., et al. (2017). Robust guar Gum/Cellulose nanofibrils multilayer films with good barrier properties. *ACS Applied Materials & Interfaces, 9*(6), 5477–5485. https://doi.org/10.1021/acsami.6b14471

Dainelli, D., Gontard, N., Spyropoulos, D., Zondervan-van den Beuken, E., & Tobback, P. (2008). Active and intelligent food packaging: Legal aspects and safety concerns. *Trends in Food Science & Technology, 19*, S103–S112. https://doi.org/10.1016/J.TIFS.2008.09.011

Dakal, T. C., Kumar, A., Majumdar, R. S., & Yadav, V. (2016). Mechanistic basis of antimicrobial actions of silver nanoparticles. *Frontiers in Microbiology, 7*, 01831. https://doi.org/10.3389/fmicb.2016.01831

de Jong, A. R., Boumans, H., Slaghek, T., Van Veen, J., Rijk, R., & Van Zandvoort, M. (2005). Active and intelligent packaging for food: Is it the future? *Food Additives and Contaminants, 22*(10), 975–979. https://doi.org/10.1080/02652030500336254

Dehnad, D., Mirzaei, H., Emam-Djomeh, Z., Jafari, S.-M., & Dadashi, S. (2014). Thermal and antimicrobial properties of chitosan–nanocellulose films for extending shelf life of ground meat. *Carbohydrate Polymers, 109*, 148–154. https://doi.org/10.1016/J.CARBPOL.2014.03.063

Dhar, P., Bhardwaj, U., Kumar, A., & Katiyar, V. (2015). Poly (3-hydroxybutyrate)/cellulose nanocrystal films for food packaging applications: Barrier and migration studies. *Polymer Engineering and Science, 55*(10), 2388–2395. https://doi.org/10.1002/pen.24127

Dhifi, W., Bellili, S., Jazi, S., Bahloul, N., & Mnif, W. (2016). Essential oils' chemical characterization and investigation of some biological activities: A critical review. *Medicines, 3*(4), 25. https://doi.org/10.3390/medicines3040025

Dong, F., Li, S. J., Liu, Z. M., & Zhu, K. X. (2015). *Improvement of quality and shelf life of strawberry with nanocellulose/chitosan composite coatings*. https://www.researchgate.net/publication/311672088_Improvement_of_quality_and_shelf_life_of_strawberry_with_nanocellulosechitosan_composite_coatings.

Dong, H., Snyder, J. F., Tran, D. T., & Leadore, J. L. (2013). Hydrogel, aerogel and film of cellulose nanofibrils functionalized with silver nanoparticles. *Carbohydrate Polymers, 95*(2), 760–767. https://doi.org/10.1016/j.carbpol.2013.03.041

Drake, P. L., & Hazelwood, K. J. (2005). Exposure-related health effects of silver and silver compounds: A review. *The Annals of Occupational Hygiene, 49*(7), 575–585. https://doi.org/10.1093/annhyg/mei019

Duval, A., & Avérous, L. (2016). Oxyalkylation of condensed tannin with propylene carbonate as an alternative to propylene oxide. *ACS Sustainable Chemistry & Engineering, 4*(6), 3103–3112. https://doi.org/10.1021/acssuschemeng.6b00081

El Miri, N., Abdelouahdi, K., Zahouily, M., Fihri, A., Barakat, A., Solhy, A., et al. (2015). Bio-nanocomposite films based on cellulose nanocrystals filled polyvinyl alcohol/chitosan polymer blend. *Journal of Applied Polymer Science, 132*(22), 42004. https://doi.org/10.1002/app.42004

Elfeky, A. S., Salem, S. S., Elzaref, A. S., Owda, M. E., Eladawy, H. A., Saeed, A. M., et al. (2020). Multifunctional cellulose nanocrystal /metal oxide hybrid, photo-degradation, antibacterial and larvicidal activities. *Carbohydrate Polymers, 230*, 115711. https://doi.org/10.1016/j.carbpol.2019.115711

El-Wakil, N. A., Hassan, E. A., Abou-Zeid, R. E., & Dufresne, A. (2015). Development of wheat gluten/nanocellulose/titanium dioxide nanocomposites for active food packaging. *Carbohydrate Polymers, 124*, 337–346. https://doi.org/10.1016/j.carbpol.2015.01.076

Errokh, A., Magnin, A., Putaux, J.-L., & Boufi, S. (2019). Hybrid nanocellulose decorated with silver nanoparticles as reinforcing filler with antibacterial properties. *Materials Science and Engineering: C, 105*, 110044. https://doi.org/10.1016/j.msec.2019.110044

Espino-Pérez, E., Bras, J., Ducruet, V., Guinault, A., Dufresne, A., & Domenek, S. (2013). Influence of chemical surface modification of cellulose nanowhiskers on thermal, mechanical, and barrier properties of poly(lactide) based bionanocomposites. *European Polymer Journal, 49*(10), 3144–3154. https://doi.org/10.1016/j.eurpolymj.2013.07.017

Fang, H., Chen, X., Wang, S., Cheng, S., & Ding, Y. (2019). Enhanced mechanical and oxygen barrier performance in biodegradable polyurethanes by incorporating cellulose nanocrystals with interfacial polylactide stereocomplexation. *Cellulose, 26*(18), 9751–9764. https://doi.org/10.1007/s10570-019-02742-0

Fang, Z., Li, B., Liu, Y., Fang, Z., Li, B., Liu, Y., et al. (2020). Critical role of degree of polymerization of cellulose in super-strong nanocellulose films. *Matter, 2*(4), 1000–1014. https://doi.org/10.1016/j.matt.2020.01.016

Farahani, H., Wagiran, R., & Hamidon, M. N. (2014). Humidity sensors principle, mechanism, and fabrication technologies: A comprehensive review. *Sensors, 14*(5), 7881–7939. https://doi.org/10.3390/s140507881

Feng, Y. H., Cheng, T. Y., Yang, W. G., Ma, P. T., He, H. Z., Yin, X. C., et al. (2018). Characteristics and environmentally friendly extraction of cellulose nanofibrils from sugarcane bagasse. *Industrial Crops and Products, 111*, 285–291. https://doi.org/10.1016/j.indcrop.2017.10.041

Ferrer, A., Pal, L., & Hubbe, M. (2017). Nanocellulose in packaging: Advances in barrier layer technologies. *Industrial Crops and Products, 95*, 574–582. https://doi.org/10.1016/J.INDCROP.2016.11.012

Fontes-Candia, C., Erboz, E., Martínez-Abad, A., López-Rubio, A., & Martínez-Sanz, M. (2019). *Food Hydrocolloids, 96*, 151–160. https://doi.org/10.1016/j.foodhyd.2019.05.011

Fortunati, E., Kenny, J. M., & Torre, L. (2019). Lignocellulosic materials as reinforcements in sustainable packaging systems. *Biomass, Biopolymer-Based Materials, and Bioenergy*, 87–102. https://doi.org/10.1016/b978-0-08-102426-3.00005-9

Fortunati, E., Armentano, I., Zhou, Q., Iannoni, A., Saino, E., Visai, L., et al. (2012). Multifunctional bionanocomposite films of poly(lactic acid), cellulose nanocrystals and silver nanoparticles. *Carbohydrate Polymers, 87*(2), 1596–1605. https://doi.org/10.1016/j.carbpol.2011.09.066

Fortunati, E., Peltzer, M., Armentano, I., Torre, L., Jiménez, A., & Kenny, J. M. (2012). Effects of modified cellulose nanocrystals on the barrier and migration properties of PLA nano-biocomposites. *Carbohydrate Polymers, 90*(2), 948–956. https://doi.org/10.1016/j.carbpol.2012.06.025

Gan, I., & Chow, W. S. (2018). Antimicrobial poly(lactic acid)/cellulose bionanocomposite for food packaging application: A review. *Food Packaging and Shelf Life, 17*, 150–161. https://doi.org/10.1016/j.fpsl.2018.06.012

Garcia-Garcia, D., Rayón, E., Carbonell-Verdu, A., Lopez-Martinez, J., & Balart, R. (2017). Improvement of the compatibility between poly(3-hydroxybutyrate) and poly(ε-caprolactone) by reactive extrusion with dicumyl peroxide. *European Polymer Journal, 86*, 41–57. https://doi.org/10.1016/j.eurpolymj.2016.11.018

Garcia-Garcia, D., Lopez-Martinez, J., Balart, R., Strömberg, E., & Moriana, R. (2018). Reinforcing capability of cellulose nanocrystals obtained from pine cones in a biodegradable poly(3-hydroxybutyrate)/poly(ε-caprolactone) (PHB/PCL) thermoplastic blend. *European Polymer Journal, 104*, 10–18. https://doi.org/10.1016/j.eurpolymj.2018.04.036

Gårdebjer, S., Bergstrand, A., Idström, A., Börstell, C., Naana, S., Nordstierna, L., et al. (2015). Solid-state NMR to quantify surface coverage and chain length of lactic acid modified cellulose nanocrystals, used as fillers in biodegradable composites. *Composites Science and Technology, 107*, 1–9. https://doi.org/10.1016/j.compscitech.2014.11.014

Gea, S., Bilotti, E., Reynolds, C. T., Soykeabkeaw, N., & Peijs, T. (2010). Bacterial cellulose-poly(vinyl alcohol) nanocomposites prepared by an in-situ process. *Materials Letters, 64*(8), 901–904. https://doi.org/10.1016/j.matlet.2010.01.042

George, J., & Siddaramaiah. (2012). High performance edible nanocomposite films containing bacterial cellulose nanocrystals. *Carbohydrate Polymers, 87*(3), 2031–2037. https://doi.org/10.1016/j.carbpol.2011.10.019

George, J., Kumar, R., Sajeevkumar, V. A., Ramana, K. V., Rajamanickam, R., Abhishek, V., et al. (2014). Hybrid HPMC nanocomposites containing bacterial cellulose nanocrystals and silver nanoparticles. *Carbohydrate Polymers, 105*(1), 285–292. https://doi.org/10.1016/j.carbpol.2014.01.057

Guo, L., Yuan, W., Lu, Z., & Li, C. M. (2013). Polymer/nanosilver composite coatings for antibacterial applications. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 439*, 69–83. https://doi.org/10.1016/j.colsurfa.2012.12.029

Hai, L. V., Choi, E. S., Zhai, L., Panicker, P. S., & Kim, J. (2020). Green nanocomposite made with chitin and bamboo nanofibers and its mechanical, thermal and biodegradable properties for food packaging. *International Journal of Biological Macromolecules, 144*, 491–499. https://doi.org/10.1016/j.ijbiomac.2019.12.124

Hambardzumyan, A., Foulon, L., Bercu, N. B., Pernes, M., Maigret, J. E., Molinari, M., et al. (2015). Organosolv lignin as natural grafting additive to improve the water resistance of films using cellulose nanocrystals. *Chemical Engineering Journal, 264*, 780–788. https://doi.org/10.1016/j.cej.2014.12.004

Han, Y., Yu, M., & Wang, L. (2018). Physical and antimicrobial properties of sodium alginate/carboxymethyl cellulose films incorporated with cinnamon essential oil. *Food Packaging and Shelf Life, 15*, 35–42. https://doi.org/10.1016/j.fpsl.2017.11.001

Hosseinnejad, M. (2014). Active packaging for food applications - A review. *International Journal of Advanced Biological and Biomedical Research, 2*(4), 1174–1180. http://www.ijabbr.com/article_7290.html.

Huang, J. Y., Li, X., & Zhou, W. (2015). Safety assessment of nanocomposite for food packaging application. *Trends in Food Science and Technology, 45*(2), 187–199. https://doi.org/10.1016/j.tifs.2015.07.002

Hubbe, M. A., Ferrer, A., Tyagi, P., Yin, Y., Salas, C., Pal, L., et al. (2017). Nanocellulose in thin films, coatings, and plies for packaging applications: A review. *BioResources, 12*(1), 2143–2233. https://doi.org/10.15376/biores.12.1.2143-2233

Huq, T., Salmieri, S., Khan, A., Khan, R. A., Le Tien, C., Riedl, B., et al. (2012). Nanocrystalline cellulose (NCC) reinforced alginate based biodegradable nanocomposite film. *Carbohydrate Polymers, 90*(4), 1757–1763. https://doi.org/10.1016/j.carbpol.2012.07.065

Ilyas, R. A., Sapuan, S. M., Ibrahim, R., Abral, H., Ishak, M. R., Zainudin, E. S., et al. (2019). Effect of sugar palm nanofibrillated cellulose concentrations on morphological, mechanical and physical properties of biodegradable films based on agro-waste sugar palm (Arenga pinnata (Wurmb.) Merr) starch. *Journal of Materials Research and Technology, 8*(5), 4819–4830. https://doi.org/10.1016/j.jmrt.2019.08.028

Jabeen, N., Majid, I., & Nayik, G. A. (2015). Bioplastics and food packaging: A review. *Cogent Food & Agriculture, 1*(1), 1117749. https://doi.org/10.1080/23311932.2015.1117749

Jacob, J., Haponiuk, J. T., Thomas, S., Peter, G., & Gopi, S. (2018). Use of ginger nanofibers for the preparation of cellulose nanocomposites and their antimicrobial activities. *Fibers, 6*(79), 1–11. https://doi.org/10.3390/fib6040079

Jiang, G., Zhang, M., Feng, J., Zhang, S., & Wang, X. (2017). High oxygen barrier property of poly(propylene carbonate)/Polyethylene glycol nanocomposites with low loading of cellulose nanocrytals. *ACS Sustainable Chemistry & Engineering, 5*(12), 11246–11254. https://doi.org/10.1021/acssuschemeng.7b01674

Kakroodi, A. R., Kazemi, Y., Nofar, M., & Park, C. B. (2017). Tailoring poly(lactic acid) for packaging applications via the production of fully bio-based in situ microfibrillar composite films. *Chemical Engineering Journal, 308*, 772–782. https://doi.org/10.1016/j.cej.2016.09.130

Kapetanakou, A. E., & Skandamis, P. N. (2016). Applications of active packaging for increasing microbial stability in foods: Natural volatile antimicrobial compounds. *Current Opinion in Food Science, 12*, 1–12. https://doi.org/10.1016/j.cofs.2016.06.001

Kargarzadeh, H., Huang, J., Lin, N., Ahmad, I., Mariano, M., Dufresne, A., et al. (2018). Recent developments in nanocellulose-based biodegradable polymers, thermoplastic polymers, and porous nanocomposites. *Progress in Polymer Science, 87*, 197–227. https://doi.org/10.1016/j.progpolymsci.2018.07.008

Karimi, N., Alizadeh, A., Almasi, H., & Hanifian, S. (2020). Preparation and characterization of whey protein isolate/polydextrose-based nanocomposite film incorporated with cellulose nanofiber and L. plantarum: A new probiotic active packaging system. *LWT, 121*, 108978. https://doi.org/10.1016/j.lwt.2019.108978

Karkhanis, S. S., Stark, N. M., Matuana, L. M., & Sabo, R. C. (2018). Water vapor and oxygen barrier properties of extrusion-blown poly(lactic acid)/cellulose nanocrystals nanocomposite films. *Composites Part A: Applied Science and Manufacturing, 114*, 204–211.

Kaushik, A., & Kaur, R. (2016). Thermoplastic starch nanocomposites reinforced with cellulose nanocrystals: Effect of plasticizer on properties. *Composite Interfaces, 23*(7), 701–717. https://doi.org/10.1080/09276440.2016.1169487

Khodayari, M., Basti, A. A., Khanjari, A., Misaghi, A., Kamkar, A., Shotorbani, P. M., et al. (2019). Effect of poly(lactic acid) films incorporated with different concentrations of Tanacetum balsamita essential oil, propolis ethanolic extract and cellulose nanocrystals on shelf life extension of vacuum-packed cooked sausages. *Food Packaging and Shelf Life, 19*, 200–209. https://doi.org/10.1016/j.fpsl.2018.11.009

Kim, T., Jeon, H., Jegal, J., Kim, J. H., Yang, H., Park, J., et al. (2018). Trans crystallization behavior and strong reinforcement effect of cellulose nanocrystals on reinforced poly(butylene succinate) nanocomposites. *RSC Advances, 8*(38), 21636. https://doi.org/10.1039/c8ra90050g

Klemm, D., Cranston, E. D., Fischer, D., Gama, M., Kedzior, S. A., Kralisch, D., et al. (2018). Nanocellulose as a natural source for groundbreaking applications in materials science: Today's state. *Materials Today, 21*(7), 720–748. https://doi.org/10.1016/j.mattod.2018.02.001. Elsevier B.V.

Koppolu, R., Abitbol, T., Kumar, V., Jaiswal, A. K., Swerin, A., & Toivakka, M. (2018). Continuous roll-to-roll coating of cellulose nanocrystals onto paperboard. *Cellulose, 25*(10), 6055–6069. https://doi.org/10.1007/s10570-018-1958-1

Koppolu, R., Lahti, J., Abitbol, T., Swerin, A., Kuusipalo, J., & Toivakka, M. (2019). Continuous processing of nanocellulose and polylactic acid into multilayer barrier coatings. *ACS Applied Materials & Interfaces, 11*(12), 11920–11927. https://doi.org/10.1021/acsami.9b00922

Kumar, V., Pathak, P., & Bhardwaj, N. K. (2020). Waste paper: An underutilized but promising source for nanocellulose mining. *Waste Management, 102*, 281–303. https://doi.org/10.1016/j.wasman.2019.10.041

Kumar, V., Elfving, A., Koivula, H., Bousfield, D., & Toivakka, M. (2016). Roll-to-Roll processed cellulose nanofiber coatings. *Industrial & Engineering Chemistry Research, 55*(12), 3603–3613. https://doi.org/10.1021/acs.iecr.6b00417

LaCoste, A., Schaich, K. M., Zumbrunnen, D., & Yam, K. L. (2005). Advancing controlled release packaging through smart blending. *Packaging Technology and Science, 18*(2), 77–87. https://doi.org/10.1002/pts.675

Lacroix, M., Criado, P., Fraschini, C., & Salmieri, S. (2014). Modification of nanocrystalline cellulose for bioactive loaded films. *Journal of Research Updates in Polymer Science, 3*(2), 122–135. https://doi.org/10.6000/1929-5995.2014.03.02.7

Lagaron, J. M., Catalá, R., & Gavara, R. (2004). Structural characteristics defining high barrier properties in polymeric materials. *Materials Science and Technology, 20*(1), 1–7. https://doi.org/10.1179/026708304225010442

Lani, N. S., Ngadi, N., Johari, A., & Jusoh, M. (2014). Isolation, characterization, and application of nanocellulose from oil palm empty fruit bunch Fiber as nanocomposites. *Journal of Nanomaterials*, 1–9. https://doi.org/10.1155/2014/702538, 2014.

Lavoine, N., Desloges, I., Khelifi, B., & Bras, J. (2014). Impact of different coating processes of microfibrillated cellulose on the mechanical and barrier properties of paper. *Journal of Materials Science, 49*(7), 2879–2893. https://doi.org/10.1007/s10853-013-7995-0

Lavoine, N., Desloges, I., Manship, B., & Bras, J. (2015). Antibacterial paperboard packaging using microfibrillated cellulose. *Journal of Food Science and Technology, 52*(9), 5590–5600. https://doi.org/10.1007/s13197-014-1675-1

Lázaro, C. A., Conte-Júnior, C. A., Monteiro, M. L. G., Canto, A. C. V. S., Costa-Lima, B. R. C., Mano, S. B., et al. (2014). Effects of ultraviolet light on biogenic amines and other quality indicators of chicken meat during refrigerated storage. *Poultry Science, 93*(9), 2304–2313. https://doi.org/10.3382/ps.2013-03642

Li, L., Bao, R. Y., Gao, T., Liu, Z. Y., Xie, B. H., Yang, M. B., et al. (2019). Dopamine-induced functionalization of cellulose nanocrystals with polyethylene glycol towards poly(L -lactic acid) bionanocomposites for green packaging. *Carbohydrate Polymers, 203*, 275–284. https://doi.org/10.1016/j.carbpol.2018.09.057

Li, P., Sirviö, J. A., Haapala, A., Khakalo, A., & Liimatainen, H. (2019). Anti-oxidative and UV-absorbing biohybrid film of cellulose nanofibrils and tannin extract. *Food Hydrocolloids, 92*, 208–217. https://doi.org/10.1016/j.foodhyd.2019.02.002

Lim, L. T. (2011). Active and intelligent packaging materials. In *Comprehensive biotechnology* (second edition,, *4* pp. 629–644). https://doi.org/10.1016/B978-0-08-088504-9.00308-1

Liu, C., Li, B., Du, H., Lv, D., Zhang, Y., Yu, G., et al. (2016). Properties of nanocellulose isolated from corncob residue using sulfuric acid, formic acid, oxidative and mechanical methods. *Carbohydrate Polymers, 151*, 716–724. https://doi.org/10.1016/j.carbpol.2016.06.025

Lokanathan, A. R., Uddin, K. M. A., Rojas, O. J., & Laine, J. (2014). Cellulose nanocrystal-mediated synthesis of silver nanoparticles: Role of sulfate groups in nucleation phenomena. *Biomacromolecules, 15*(1), 373–379. https://doi.org/10.1021/bm401613h

Long, K., Cha, R., Zhang, Y., Li, J., Ren, F., & Jiang, X. (2018). Cellulose nanocrystals as reinforcements for collagen-based casings with low gas transmission. *Cellulose, 25*(1), 463–471. https://doi.org/10.1007/s10570-017-1569-2

López de Dicastillo, C., Nerín, C., Alfaro, P., Catalá, R., Gavara, R., & Hernández-Muñoz, P. (2011). Development of new antioxidant active packaging films based on ethylene vinyl alcohol copolymer (EVOH) and green tea extract. *Journal of Agricultural and Food Chemistry, 59*(14), 7832–7840. https://doi.org/10.1021/jf201246g

Luo, J., Zhang, M., Yang, B., Liu, G., Tan, J., Nie, J., et al. (2019). A promising transparent and UV-shielding composite film prepared by aramid nanofibers and nanofibrillated cellulose. *Carbohydrate Polymers, 203*, 110–118. https://doi.org/10.1016/j.carbpol.2018.09.040

Luzi, F., Fortunati, E., Jiménez, A., Puglia, D., Pezzolla, D., Gigliotti, G., et al. (2016). Production and characterization of PLA_PBS biodegradable blends reinforced with cellulose nanocrystals extracted from hemp fibres. *Industrial Crops and Products, 93*, 276–289. https://doi.org/10.1016/j.indcrop.2016.01.045

Ma, Q., Cao, L., Liang, T., Li, J., Lucia, L. A., & Wang, L. (2018). Active Tara gum/pva blend films with curcumin-loaded CTAC Brush-TEMPO-Oxidized cellulose nanocrystals. *ACS Sustainable Chemistry and Engineering, 6*(7), 8926–8934. https://doi.org/10.1021/acssuschemeng.8b01281

Maliha, M., Herdman, M., Brammananth, R., McDonald, M., Coppel, R., Werrett, M., et al. (2020). Bismuth phosphinate incorporated nanocellulose sheets with antimicrobial and barrier properties for packaging applications. *Journal of Cleaner Production*, 119016. https://doi.org/10.1016/j.jclepro.2019.119016

Mascheroni, E., Rampazzo, R., Ortenzi, M. A., Piva, G., Bonetti, S., & Piergiovanni, L. (2016). Comparison of cellulose nanocrystals obtained by sulfuric acid hydrolysis and ammonium persulfate, to be used as coating on flexible food-packaging materials. *Cellulose, 23*(1), 779–793. https://doi.org/10.1007/s10570-015-0853-2

Mastromatteo, M., Mastromatteo, M., Conte, A., & Del Nobile, M. A. (2010). Advances in controlled release devices for food packaging applications. *Trends in Food Science & Technology, 21*(12), 591–598. https://doi.org/10.1016/j.tifs.2010.07.010. Elsevier.

Miller, K. S., & Krochta, J. M. (1997). Oxygen and aroma barrier properties of edible films: A review. *Trends in Food Science & Technology, 8*(7), 228–237. https://doi.org/10.1016/S0924-2244(97)01051-0. Elsevier Science Ltd.

Missio, A. L., Mattos, B. D., Ferreira, D., de, F., Magalhães, W. L. E., Bertuol, D. A., et al. (2018). Nanocellulose-tannin films: From trees to sustainable active packaging. *Journal of Cleaner Production, 184*, 143–151. https://doi.org/10.1016/j.jclepro.2018.02.205

Mondragon, G., Peña-Rodriguez, C., González, A., Eceiza, A., & Arbelaiz, A. (2015). Bionanocomposites based on gelatin matrix and nanocellulose. *European Polymer Journal, 62*, 1–9. https://doi.org/10.1016/j.eurpolymj.2014.11.003

Morelli, C. L., Belgacem, M. N., Branciforti, M. C., Bretas, R. E. S., Crisci, A., & Bras, J. (2016). Supramolecular aromatic interactions to enhance biodegradable film properties through incorporation of functionalized cellulose nanocrystals. *Composites Part A: Applied Science and Manufacturing, 83*, 80–88. https://doi.org/10.1016/j.compositesa.2015.10.038

Morelli, C. L., Belgacem, N., Bretas, R. E. S., & Bras, J. (2016). Melt extruded nanocomposites of polybutylene adipate-co-terephthalate (PBAT) with phenylbutyl isocyanate modified cellulose nanocrystals. *Journal of Applied Polymer Science, 133*(34), 1–9. https://doi.org/10.1002/app.43678

Moustafa, H., Youssef, A. M., Darwish, N. A., & Abou-Kandil, A. I. (2019). Eco-friendly polymer composites for green packaging: Future vision and challenges. *Composites Part B: Engineering, 172*, 16–25. https://doi.org/10.1016/j.compositesb.2019.05.048

Nair, S. S., Zhu, J., Deng, Y., & Ragauskas, A. J. (2014). High performance green barriers based on nanocellulose. *Sustainable Chemical Processes, 2*(1), 23. https://doi.org/10.1186/s40508-014-0023-0

Nguyen Van Long, N., Joly, C., & Dantigny, P. (2016). Active packaging with antifungal activities. *International Journal of Food Microbiology, 220*, 73–90. https://doi.org/10.1016/j.ijfoodmicro.2016.01.001

Olarte, C., Sanz, S., Federico Echávarri, J., & Ayala, F. (2009). Effect of plastic permeability and exposure to light during storage on the quality of minimally processed broccoli and cauliflower. *LWT - Food Science and Technology, 42*(1), 402–411. https://doi.org/10.1016/j.lwt.2008.07.001

Osong, S. H., Norgren, S., & Engstrand, P. (2016). Processing of wood-based microfibrillated cellulose and nanofibrillated cellulose, and applications relating to papermaking: A review. *Cellulose, 23*(1), 93–123. https://doi.org/10.1007/s10570-015-0798-5

Panaitescu, D. M., Frone, A. N., & Chiulan, I. (2016). Nanostructured biocomposites from aliphatic polyesters and bacterial cellulose. *Industrial Crops and Products, 93*, 251–266. https://doi.org/10.1016/j.indcrop.2016.02.038

Panaitescu, D. M., Ionita, E. R., Nicolae, C. A., Gabor, A. R., Ionita, M. D., Trusca, R., et al. (2018). Poly(3-hydroxybutyrate) modified by nanocellulose and plasma treatment for packaging applications. *Polymers, 10*(11), 1–24. https://doi.org/10.3390/polym10111249

Park, J. M. (2005). Paper and paperboard packaging. In *Handbook of food science, technology, and engineering, 4* pp. 2382–2387). https://doi.org/10.1533/9780857095701.2.178

Parry, R. T. (1993). Principles and applications of modified atmosphere packaging of foods. *Principles and applications of modified atmosphere packaging of foods*. https://doi.org/10.1007/978-1-4615-2137-2

Paunonen, S. (2013). Strength and barrier enhancements of cellophane and cellulose derivative films: A review. *BioResources, 8*(2), 3098–3121.

Peelman, N., Ragaert, P., Ragaert, K., De Meulenaer, B., Devlieghere, F., & Cardon, L. (2015). Heat resistance of new biobased polymeric materials, focusing on starch, cellulose, PLA, and PHA. *Journal of Applied Polymer Science, 132*(48), 42305. https://doi.org/10.1002/app.42305

Pei, A., Zhou, Q., & Berglund, L. A. (2010). Functionalized cellulose nanocrystals as biobased nucleation agents in poly(l-lactide) (PLLA) - Crystallization and mechanical property effects. *Composites Science and Technology, 70*(5), 815–821. https://doi.org/10.1016/j.compscitech.2010.01.018

Peng, B., Zhang, H., & Zhang, Y. (2019). Investigation of the relationship between functional groups evolution and combustion kinetics of microcrystalline cellulose using in situ DRIFTS. *Fuel, 248*, 56–64. https://doi.org/10.1016/j.fuel.2019.03.069

Pinheiro, I. F., Ferreira, F. V., Souza, D. H. S., Gouveia, R. F., Lona, L. M. F., Morales, A. R., et al. (2017). Mechanical, rheological and degradation properties of PBAT nanocomposites reinforced by functionalized cellulose nanocrystals. *European Polymer Journal, 97*, 356–365. https://doi.org/10.1016/j.eurpolymj.2017.10.026

Poole, C. P., & Owens, F. J. (2003). *Introduction to nanotechnology*. New York: John Wiley and Sons.

Portela da Gama, F. M., & Dourado, F. (2018). Bacterial nanocellulose: what future? *BioImpacts: BI, 8*(1), 1–3. https://doi.org/10.15171/bi.2018.01

Pourjavaher, S., Almasi, H., Meshkini, S., Pirsa, S., & Parandi, E. (2017). Development of a colorimetric pH indicator based on bacterial cellulose nanofibers and red cabbage (Brassica oleraceae) extract. *Carbohydrate Polymers, 156*, 193–201. https://doi.org/10.1016/j.carbpol.2016.09.027

Poyatos-Racionero, E., Ros-Lis, J. V., Vivancos, J. L., & Martínez-Máñez, R. (2018). Recent advances on intelligent packaging as tools to reduce food waste. *Journal of Cleaner Production, 172*, 3398–3409. https://doi.org/10.1016/j.jclepro.2017.11.075

Prabhu, S., & Poulose, E. K. (2012). Silver nanoparticles: Mechanism of antimicrobial action, synthesis, medical applications, and toxicity effects. *International Nano Letters, 2*(1), 1–10. https://doi.org/10.1186/2228-5326-2-32

Quintavalla, S., & Vicini, L. (2002). Antimicrobial food packaging in meat industry. *Meat Science, 62*(3), 373–380. https://doi.org/10.1016/S0309-1740(02)00121-3

Rajinipriya, M., Nagalakshmaiah, M., Robert, M., & Elkoun, S. (2018). Importance of agricultural and industrial waste in the field of nanocellulose and recent industrial developments of wood based nanocellulose: A review. *ACS Sustainable Chemistry and Engineering, 6*(3), 2807–2828. https://doi.org/10.1021/acssuschemeng.7b03437. American Chemical Society.

Rampazzo, R., Alkan, D., Gazzotti, S., Ortenzi, M. A., Piva, G., & Piergiovanni, L. (2017). Cellulose nanocrystals from lignocellulosic raw materials, for oxygen barrier coatings on food packaging films. *Packaging Technology and Science, 30*(10), 645–661. https://doi.org/10.1002/pts.2308

Reddy, J. P., & Rhim, J. W. (2014). Characterization of bionanocomposite films prepared with agar and paper-mulberry pulp nanocellulose. *Carbohydrate Polymers, 110*, 480–488. https://doi.org/10.1016/j.carbpol.2014.04.056

Ribeiro-Santos, R., Andrade, M., & Sanches-Silva, A. (2017). Application of encapsulated essential oils as antimicrobial agents in food packaging. *Current Opinion in Food Science, 14*, 78–84. https://doi.org/10.1016/j.cofs.2017.01.012. Elsevier Ltd.

Rodionova, G., Lenes, M., Eriksen, Ø., & Gregersen, Ø. (2011). Surface chemical modification of microfibrillated cellulose: Improvement of barrier properties for packaging applications. *Cellulose, 18*(1), 127–134. https://doi.org/10.1007/s10570-010-9474-y

Rol, F., Belgacem, M. N., Gandini, A., & Bras, J. (2019). Recent advances in surface-modified cellulose nanofibrils. *Progress in Polymer Science, 88*, 241–264. https://doi.org/10.1016/j.progpolymsci.2018.09.002

Sadeghifar, H., Venditti, R., Jur, J., Gorga, R. E., & Pawlak, J. J. (2017). Cellulose-lignin biodegradable and flexible UV protection film. *ACS Sustainable Chemistry and Engineering, 5*(1), 625–631. https://doi.org/10.1021/acssuschemeng.6b02003

Salari, M., Sowti Khiabani, M., Rezaei Mokarram, R., Ghanbarzadeh, B., & Samadi Kafil, H. (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

Salmieri, S., Islam, F., Khan, R. A., Hossain, F. M., Ibrahim, H. M. M., Miao, C., et al. (2014). Antimicrobial nanocomposite films made of poly(lactic acid)–Cellulose nanocrystals (PLA–CNC) in food applications—Part B: Effect of oregano essential oil release on the inactivation of Listeria monocytogenes in mixed vegetables. *Cellulose, 21*(6), 4271–4285. https://doi.org/10.1007/s10570-014-0406-0

Sanchez-Garcia, M. D., Lopez-Rubio, A., & Lagaron, J. M. (2010). Natural micro and nanobiocomposites with enhanced barrier properties and novel functionalities for food biopackaging applications. *Trends in Food Science & Technology, 21*(11), 528–536. https://doi.org/10.1016/j.tifs.2010.07.008

Santana, J. S., de Carvalho Costa, É. K., Rodrigues, P. R., Correia, P. R. C., Cruz, R. S., & Druzian, J. I. (2019). Morphological, barrier, and mechanical properties of cassava starch films reinforced with cellulose and starch nanoparticles. *Journal of Applied Polymer Science, 136*(4), 47001. https://doi.org/10.1002/app.47001

Santos, T. M., Filho, S., M. de, S. M., Caceres, C. A., Rosa, M. F., Morais, J. P. S., et al. (2014). Fish gelatin films as affected by cellulose whiskers and sonication. *Food Hydrocolloids, 41*, 113–118. https://doi.org/10.1016/j.foodhyd.2014.04.001

Sarwar, M. S., Niazi, M. B. K., Jahan, Z., Ahmad, T., & Hussain, A. (2018). Preparation and characterization of PVA/nanocellulose/Ag nanocomposite films for antimicrobial food packaging. *Carbohydrate Polymers, 184*(January), 453–464. https://doi.org/10.1016/j.carbpol.2017.12.068

Saxena, A., & Ragauskas, A. J. (2009). Water transmission barrier properties of biodegradable films based on cellulosic whiskers and xylan. *Carbohydrate Polymers, 78*(2), 357–360. https://doi.org/10.1016/j.carbpol.2009.03.039

Schade, M., Weinkoetz, S., & Assmann, J. (2015). Lignocellulosic material useful for producing articles e.g. packaging materials, comprises lignocellulose-containing material, microfibrillated cellulose, binder optionally with curing agent, expanded plastic particles, and additives (Patent No. WO2015052028-A1).

Schaider, L. A., Balan, S. A., Blum, A., Andrews, D. Q., Strynar, M. J., Dickinson, M. E., et al. (2017). Fluorinated compounds in U.S. fast food packaging. *Environmental Science & Technology Letters, 4*(3), 105–111. https://doi.org/10.1021/acs.estlett.6b00435

Shankar, S., & Rhim, J. W. (2016). Preparation of nanocellulose from micro-crystalline cellulose: The effect on the performance and properties of agar-based composite films. *Carbohydrate Polymers, 135*, 18–26. https://doi.org/10.1016/j.carbpol.2015.08.082

Shanmugam, K., Doosthosseini, H., Varanasi, S., Garnier, G., & Batchelor, W. (2019). Nanocellulose films as air and water vapour barriers: A recyclable and biodegradable alternative to polyolefin packaging. *Sustainable Materials and Technologies, 22*, e00115. https://doi.org/10.1016/j.susmat.2019.e00115

Shanmugam, K., Varanasi, S., Garnier, G., & Batchelor, W. (2017). Rapid preparation of smooth nanocellulose films using spray coating. *Cellulose, 24*(7), 2669–2676. https://doi.org/10.1007/s10570-017-1328-4

Sharma, C., & Bhardwaj, N. K. (2019). Fabrication of natural-origin antibacterial nanocellulose films using bio-extracts for potential use in biomedical industry. *International Journal of Biological Macromolecules*. https://doi.org/10.1016/j.ijbiomac.2019.09.182

Sharma, D., & Dhanjal, D. S. (2016). Bio-nanotechnology for active food packaging. *Journal of Applied Pharmaceutical Science, 6*(9), 220–226. https://doi.org/10.7324/JAPS.2016.60933

Sharma, A., Thakur, M., Bhattacharya, M., Mandal, T., & Goswami, S. (2019). Commercial application of cellulose nano-composites – A review. *Biotechnology Reports, 21*, Article e00316. https://doi.org/10.1016/j.btre.2019.e00316

Sharma, S., Zhang, X., Nair, S. S., Ragauskas, A., Zhu, J., & Deng, Y. (2014). Thermally enhanced high performance cellulose nano fibril barrier membranes. *RSC Advances, 4*(85), 45136–45142. https://doi.org/10.1039/c4ra07469f

Silva-Weiss, A., Bifani, V., Ihl, M., Sobral, P. J. A., & Gómez-Guillén, M. C. (2013). Structural properties of films and rheology of film-forming solutions based on chitosan and chitosan-starch blend enriched with murta leaf extract. *Food Hydrocolloids, 31*(2), 458–466. https://doi.org/10.1016/j.foodhyd.2012.11.028

Silvestre, C., Duraccio, D., & Cimmino, S. (2011). Food packaging based on polymer nanomaterials. *Progress in Polymer Science, 36*(12), 1766–1782. https://doi.org/10.1016/j.progpolymsci.2011.02.003

Sobhan, A., Muthukumarappan, K., Cen, Z., & Wei, L. (2019). Characterization of nanocellulose and activated carbon nanocomposite films' biosensing properties for smart packaging. *Carbohydrate Polymers, 225*, 115189. https://doi.org/10.1016/j.carbpol.2019.115189

Sogut, E. (2020). Active whey protein isolate films including bergamot oil emulsion stabilized by nanocellulose. *Food Packaging and Shelf Life, 23*, 100430. https://doi.org/10.1016/j.fpsl.2019.100430

Su, Q. Z., Lin, Q. B., Chen, C. F., Wu, L. B., & Wang, Z. W. (2017). Effect of organic additives on silver release from nanosilver–polyethylene composite films to acidic food simulant. *Food Chemistry, 228*, 560–566. https://doi.org/10.1016/j.foodchem.2017.01.148

Sukyai, P., Anongjanya, P., Bunyahwuthakul, N., Kongsin, K., Harnkarnsujarit, N., Sukatta, U., et al. (2018). Effect of cellulose nanocrystals from sugarcane bagasse on whey protein isolate-based films. *Food Research International, 107*, 528–535. https://doi.org/10.1016/j.foodres.2018.02.052

Sun, H., Shao, X., Zhang, M., Wang, Z., Dong, J., & Yu, D. (2019). Mechanical, barrier and antimicrobial properties of corn distarch phosphate/nanocrystalline cellulose films incorporated with Nisin and ε-polylysine. *International Journal of Biological Macromolecules, 136*, 839–846. https://doi.org/10.1016/j.ijbiomac.2019.06.134

Syverud, K., & Stenius, P. (2009). Strength and barrier properties of MFC films. *Cellulose, 16*(1), 75–85. https://doi.org/10.1007/s10570-008-9244-2

Takala, P. N., Salmieri, S., Boumail, A., Khan, R. A., Vu, K. D., Chauve, G., et al. (2013). Antimicrobial effect and physicochemical properties of bioactive trilayer polycaprolactone/methylcellulose-based films on the growth of foodborne pathogens and total microbiota in fresh broccoli. *Journal of Food Engineering, 116*(3), 648–655. https://doi.org/10.1016/j.jfoodeng.2013.01.005

Talón, E., Trifkovic, K. T., Nedovic, V. A., Bugarski, B. M., Vargas, M., Chiralt, A., et al. (2017). Antioxidant edible films based on chitosan and starch containing polyphenols from thyme extracts. *Carbohydrate Polymers, 157*, 1153–1161. https://doi.org/10.1016/j.carbpol.2016.10.080

Tyagi, P., Lucia, L. A., Hubbe, M. A., & Pal, L. (2019). Nanocellulose-based multilayer barrier coatings for gas, oil, and grease resistance. *Carbohydrate Polymers, 206*, 281–288. https://doi.org/10.1016/j.carbpol.2018.10.114

Vähä-Nissi, M., Koivula, H. M., Räisänen, H. M., Vartiainen, J., Ragni, P., Kenttä, E., et al. (2017). Cellulose nanofibrils in biobased multilayer films for food packaging. *Journal of Applied Polymer Science, 134*(19), 44830. https://doi.org/10.1002/app.44830

Vartiainen, J., Kaijunen, T., Nykanen, H., Maim, T., & Tammelin, T. (2014). Improving multilayer packaging performance with nanocellulose barrier layer. *TAPPI PLACE Conference*, 763–790. https://www.researchgate.net/publication/289855667_Improving_multilayer_packaging_performance_with_nanocellulose_barrier_layer.

Vartiainen, J., Shen, Y., Kaljunen, T., Malm, T., Vähä-Nissi, M., Putkonen, M., et al. (2016). Bio-based multilayer barrier films by extrusion, dispersion coating and atomic layer deposition. *Journal of Applied Polymer Science, 133*(2), 42260. https://doi.org/10.1002/app.42260

Vilarinho, F., Sanches Silva, A., Vaz, M. F., & Farinha, J. P. (2018). Nanocellulose in green food packaging. *Critical Reviews in Food Science and Nutrition, 58*(9), 1526–1537. https://doi.org/10.1080/10408398.2016.1270254

Vilela, C., Moreirinha, C., Domingues, E. M., Figueiredo, F. M. L., Almeida, A., & Freire, C. S. R. (2019). Antimicrobial and conductive nanocellulose-based films for active and intelligent food packaging. *Nanomaterials, 9*(7), 1–16. https://doi.org/10.3390/nano9070980

Vizireanu, S., Panaitescu, D. M., Nicolae, C. A., Frone, A. N., Chiulan, I., Ionita, M. D., et al. (2018). Cellulose defibrillation and functionalization by plasma in liquid treatment. *Scientific Reports, 8*(1), 33687. https://doi.org/10.1038/s41598-018-33687-2

Wang, H., & Wang, L. (2017). Developing a bio-based packaging film from soya by-products incorporated with valonea tannin. *Journal of Cleaner Production, 143*, 624–633. https://doi.org/10.1016/j.jclepro.2016.12.064

Wang, W., Yu, Z., Alsammarraie, F. K., Kong, F., Lin, M., & Mustapha, A. (2019). Properties and antimicrobial activity of polyvinyl alcohol-modified bacterial nanocellulose packaging films incorporated with silver nanoparticles. *Food Hydrocolloids, 100*, 105411. https://doi.org/10.1016/j.foodhyd.2019.105411

Wang, J., Gardner, D. J., Stark, N. M., Bousfield, D. W., Tajvidi, M., & Cai, Z. (2018). Moisture and oxygen barrier properties of cellulose nanomaterial-based films. *ACS Sustainable Chemistry & Engineering, 6*(1), 49–70. https://doi.org/10.1021/acssuschemeng.7b03523

Wang, X., Xie, Y., Ge, H., Chen, L., Wang, J., Zhang, S., et al. (2018). Physical properties and antioxidant capacity of chitosan/epigallocatechin-3-gallate films reinforced with nano-bacterial cellulose. *Carbohydrate Polymers, 179*, 207–220. https://doi.org/10.1016/j.carbpol.2017.09.087

Wu, B., Geng, B., Chen, Y., Liu, H., Li, G., & Wu, Q. (2017). Preparation and characteristics of TEMPO-oxidized cellulose nanofibrils from bamboo pulp and their oxygen-barrier application in PLA films. *Frontiers of Chemical Science and Engineering, 11*(4), 554–563. https://doi.org/10.1007/s11705-017-1673-8

Wu, J., Zheng, Y., Song, W., Luan, J., Wen, X., Wu, Z., et al. (2014). In situ synthesis of silver-nanoparticles/bacterial cellulose composites for slow-released antimicrobial wound dressing. *Carbohydrate Polymers, 102*(1), 762–771. https://doi.org/10.1016/j.carbpol.2013.10.093

Wu, Z., Deng, W., Luo, J., & Deng, D. (2019). Multifunctional nano-cellulose composite films with grape seed extracts and immobilized silver nanoparticles. *Carbohydrate Polymers, 205*, 447–455. https://doi.org/10.1016/j.carbpol.2018.10.060

Yang, W., Fortunati, E., Dominici, F., Giovanale, G., Mazzaglia, A., Balestra, G. M., et al. (2016). Synergic effect of cellulose and lignin nanostructures in PLA based systems for food antibacterial packaging. *European Polymer Journal, 79*, 1–12. https://doi.org/10.1016/J.EURPOLYMJ.2016.04.003

Yang, Z., Zhang, S., Tarabara, V. V., & Bruening, M. L. (2018). Aqueous swelling of zwitterionic poly(sulfobetaine methacrylate) brushes in the presence of ionic surfactants. *Macromolecules, 51*(3), 1161–1171. https://doi.org/10.1021/acs.macromol.7b01830

Yu, H., Yan, C., & Yao, J. (2014). Fully biodegradable food packaging materials based on functionalized cellulose nanocrystals/poly(3-hydroxybutyrate-co-3-hydroxyvalerate) nanocomposites. *RSC Advances, 4*(104), 59792–59802. https://doi.org/10.1039/c4ra12691b

Zeng, M., Laromaine, A., Feng, W., Levkin, P. A., & Roig, A. (2014). Origami magnetic cellulose: Controlled magnetic fraction and patterning of flexible bacterial cellulose. *Journal of Materials Chemistry C, 2*(31), 6312–6318. https://doi.org/10.1039/c4tc00787e

Zhang, X., Ma, P., & Y. Z. (2016). Structure and properties of surface-acetylated cellulose nanocrystal/poly(butylene adipate-co-terephthalate) composites. *Polymer, 73*, 2073–2085.

Zhang, H., Yu, H.-Y., Wang, C., & Yao, J. (2017). Effect of silver contents in cellulose nanocrystal/silver nanohybrids on PHBV crystallization and property improvements. *Carbohydrate Polymers, 173*, 7–16. https://doi.org/10.1016/J.CARBPOL.2017.05.064

Zhao, K., Wang, W., Teng, A., Zhang, K., Ma, Y., Duan, S., et al. (2020). Using cellulose nanofibers to reinforce polysaccharide films: Blending vs layer-by-layer casting. *Carbohydrate Polymers, 227*, 115264. https://doi.org/10.1016/j.carbpol.2019.115264

Zhao, Y., Simonsen, J., Cavender, G., Jung, J., & Fuchigami, L. H. (2014). *Nano-cellulose coatings to prevent damage in foodstuffs (Patent No. US 20140272013)*.

Zhilong, Y., Alsammarraie, F. K., Nayigiziki, F. X., Wang, W., Vardhanabhuti, B., Mustapha, A., et al. (2017). Effect and mechanism of cellulose nanofibrils on the active functions of biopolymer-based nanocomposite films. *Food Research International, 99*, 166–172. https://doi.org/10.1016/J.FOODRES.2017.05.009

Zhilong, Y., Dhital, R., Wang, W., Sun, L., Zeng, W., Mustapha, A., et al. (2019). Development of multifunctional nanocomposites containing cellulose nanofibrils and soy proteins as food packaging materials. *Food Packaging and Shelf Life, 21*, 100366. https://doi.org/10.1016/j.fpsl.2019.100366

Zhilong, Y., Wang, W., Kong, F., Lin, M., & Mustapha, A. (2019). Cellulose nanofibril/silver nanoparticle composite as an active food packaging system and its toxicity to human colon cells. *International Journal of Biological Macromolecules, 129*, 887–894. https://doi.org/10.1016/j.ijbiomac.2019.02.084

Zick, S. M., Djuric, Z., Ruffin, M. T., Litzinger, A. J., Normolle, D. P., Alrawi, S., et al. (2008). Pharmacokinetics of 6-gingerol, 8-gingerol, 10-gingerol, and 6-shogaol and conjugate metabolites in healthyhuman subjects. *Cancer Epidemiology Biomarkers and Prevention, 17*(8), 1930–1936. https://doi.org/10.1158/1055-9965.EPI-07-2934