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COMPREHENSIVE REVIEW

Application of cellulose- and chitosan-based edible coatings for quality and safety of deep-fried foods

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Abstract

Excessive oil uptake and formation of carcinogens, such as acrylamide (AA), heterocyclic amines (HCAs), and polycyclic aromatic hydrocarbons (PAHs), during deep-frying are a potential threat for food quality and safety. Cellulose- and chitosan-based edible coatings have been widely applied to deep-fried foods for reduction of oil uptake because of their barrier property to limit oil ingress, and their apparent inhibition of AA formation. Cellulose- and chitosan-based edible coatings have low negative impacts on sensory attributes of fried foods and are low cost, nontoxic, and nonallergenic. They also show great potential for reducing HCAs and PAHs in fried foods. The incorporation of nanoparticles improves mechanical and barrier properties of cellulose and chitosan coatings, which may also contribute to reducing carcinogens derived from deep-frying. Considering the potential for positive health outcomes, cellulose- and chitosan-based edible coatings could be a valuable method for the food industry to improve the quality and safety of deep-fried foods.

KEYWORDS

acrylamide, cellulose, chitosan, deep-frying, edible coating, heterocyclic amines, oil uptake, polycyclic aromatic hydrocarbons

1 | INTRODUCTION

Consumer demand for deep-fried food products is attributed to their characteristic crispy crust and unique taste and flavor developed during the deep-frying process (Soto-Jover et al., 2016). However, regular consumption of deep-fried foods may increase the risk of chronic diseases, such as diabetes, obesity, cardiovascular disease, and cancer (Brouwer, 2020). These health issues could be attributed to the high oil content of the fried foods and carcinogens formed during the deep-frying process, including acrylamide (AA), heterocyclic amines (HCAs), and polycyclic aromatic hydrocarbons (PAHs).

The application of edible coatings prior to frying has been shown to be an effective strategy for reducing oil uptake in foods (Hashim et al., 2020; Martínez-Pineda et al., 2021). Edible coatings are commonly made with food-grade polysaccharide-based hydrocolloids such as methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), carboxymethylcellulose (CMC), and protein-based hydrocolloids, such as soy protein isolate (SPI) and whey protein isolate. These hydrocolloids form a thin layer on the food surface and are regarded as an effective oil reduction method due to their action as a barrier against lipid absorption by the food (Albert & Mittal, 2002; Ananey-Obiri et al., 2018).

In the last few years, researchers have developed advanced coating materials, comprising nanoparticles and composites to further improve the functional properties of edible coatings (Ali et al., 2011; Jeya Jeevahan et al., 2020; Trajkovska Petkoska et al., 2021). However, considerations of the potential consequences on health related to the ingestion of chemical compounds within the coated fried foods are still limited. Kurek et al. (2017) reported that edible coatings, such as pectin coatings, could inhibit the formation of AA in fried banana chips. Similarly, cellulose- and chitosan-based coatings were found to inhibit AA formation during deep-frying; furthermore, these materials had the potential to reduce HCA and PAH contents in deep-fried foods (Wang et al., 2022; Zhang et al., 2021). As this aspect has not yet been fully investigated, the current review aims to provide an overview of oil uptake and formation of AAs, HCAs, and PAHs in deep-fried foods. The application of cellulose- and chitosan-based edible coatings for oil and AA reduction, including their impacts on sensory attributes of fried foods and advantages, is discussed. In addition, this review also provides comprehensive insights into the potential of cellulose- and chitosan-based edible coatings for the reduction of HCAs and PAHs in fried foods and applications of nanoparticles to enhance the coating performance, such as tensile strength, water barrier properties, and reduction of oil uptake during frying.

2 | PHYSICAL AND CHEMICAL CHANGES DUE TO DEEP-FRYING OF FOOD

Deep-frying is the process of immersing food in edible oil or fat at an elevated temperature well above the boiling point of water. Frying in oil contributes to the unique sensory characteristics of flavor, aroma, taste, and texture, which consumers highly desire. However, the process of deep-frying leads to oil uptake and the formation of carcinogenic chemicals affecting both the quality and safety of the foods.

2.1 | Mechanisms of oil uptake in three oil faction model during frying

During deep-frying of food, heat and mass transfer occurs between the food and the frying oil. Many scholars have provided comprehensive insights into the mechanisms of oil uptake to explain how water is lost and oil is absorbed throughout the deep-frying process, mainly including considerations of capillary mechanism, water replacement, cooling-phase effect, and adherence and drainage (Kurek et al., 2017; Liberty et al., 2019; Mellema, 2003). Bouchon et al. (2003) classified the absorbed oil into three fractions: structural oil (STO; the oil absorbed during frying), penetrated surface oil (PSO; the oil absorbed into the food during cooling after removal from the fryer), and surface oil (SO; the oil that remains on the surface of the fried food). This oil fraction model illustrates where and when the oil is absorbed, which has been used in many studies to analyze the distribution of oil uptake, such as listed in Figure 1 (Jia et al., 2017; Pedreschi et al., 2008; Zhang et al., 2016).

Figure 2 illustrates the association between the mechanisms of oil uptake and the oil fraction model. When food is first placed into deep-frying, water escapes into the frying oil through capillaries on the surface of the food, forming bubbles around the food, and the oil begins to fill the voids left by water. This mechanism of oil uptake is known as water replacement, in which the STO is absorbed because of water loss (Ananey-Obiri et al., 2018; Liberty et al., 2019). Due to surface dehydration, the frying interface moves inward, creating a thin layer of crust on the food surface that causes increased pressure inside the food, which together inhibit the food's ability to absorb oil (Bouchon et al., 2003). This was observed in fried potato chips in that up to 80% of the moisture loss occurred during the first 4 min, but the STO was only increased by about 5% (Zhang et al., 2016). After most of the moisture was lost, the internal pressure decreased, resulting in a less inhibitory effect on the STO uptake. As shown in Figure 1, for potato chips, the proportion of STO increases sharply after 4 min until the moisture content of potato chips reaches an equilibrium (8–12 min) (Zhang et al., 2016). The uptake of STO obeys the mechanism of water replacement, which is essentially forced by the vapor pressure, as described by Mellema (2003) based on the capillary mechanism.

During the cooling phase of frying, oil uptake is still progressing via capillary forces. When the fried product is removed from the fryer, some oil remains on the surface of the fried food, that is, the SO (Bouchon et al., 2003). Ziaiifar et al. (2008) defined the mechanism of SO uptake as adherence and drainage (Figure 2), because the absorption of SO is a balance between the adhesion force for the oil on the food that depends on the capillary pressure and drainage of the oil from the food by gravity. When the decreased vapor pressure on the interface after heating terminates, most SO would be sucked into the interior as the PSO. Therefore, the SO is typically the smallest oil fraction, accounting for less than 5% of total oil uptake in

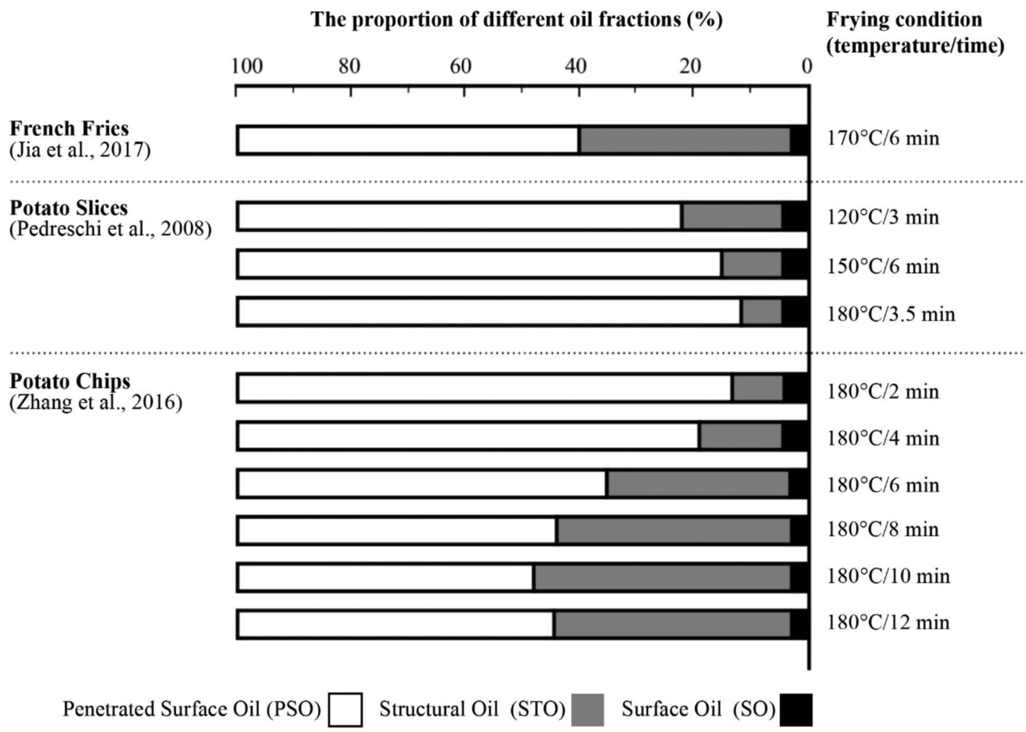

FIGURE 1 The proportion of different oil fractions in selected oil fried foods

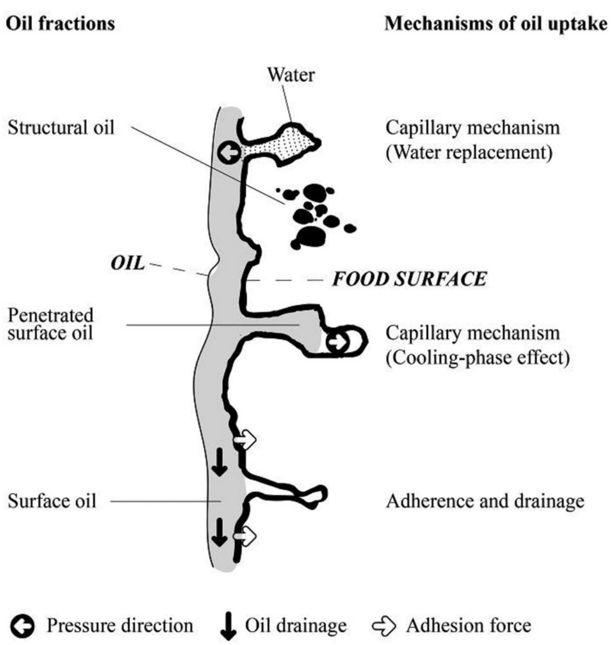

FIGURE 2 Illustration of oil fractions and relative mechanisms of oil uptake during food frying

deep-fried foods (Figure 1). This "vacuum-like" oil suction (uptake of PSO) during the cooling phase is referred to as the cooling-phase effect (Ananey-Obiri et al., 2018; Liberty et al., 2019), which can be readily visualized by the uptake of a dyed oil (Bouchon et al., 2003; Zhang et al., 2018). Most of the voids in the food left in the immersion frying phase will be replaced by the PSO during the postfrying phase (Bouchon et al., 2003). As shown in Figure 1, PSO accounted for up to 85% of the total oil uptake in the fried potato slices (Pedreschi et al., 2008).

Oil uptake can be influenced by the frying time and temperature, moisture content, surface characteristics (e.g., area, roughness, and porosity), and thickness of the raw food, as well as the viscosity of frying oil (Debnath et al., 2003; Krokida et al., 2000; Ziaiifar et al., 2008). When deep-frying food at optimum temperature and time, the rapid dehydration on the food surface results in a unique texture, that is, a crispy crust and a soft and moist interior. However, excessive oil absorption can cause a soggy texture in food that is over-fried (Choe & Min, 2007). Moreover, oil can carry hydrophobic compounds, such as PAHs, into foods during oil uptake, which is described in the following section.

2.2 | Formation of carcinogenic chemicals

The European Food Safety Authority (EFSA, 2008, 2015) and International Agency for Research on Cancer (IARC, 1993) classified AA, HCAs, and PAHs as three key carcinogens that can be formed during food heat processing, such as deep-frying. According to Regulation (EC)

No. 1881/2006 by the European Commission, the maximum levels of benzo[a]pyrene, a typical PAH, range from 1.0 to 10.0 μg/kg wet weight in foods (EFSA, 2008). Although there are no legislative limits for AA or HCAs, the daily intake of AA and HCAs was recommended to be below 1 μg/kg body weight and 0.15 μg per person, respectively (EFSA, 2015; Nohmi & Watanabe, 2021). The formation of these carcinogenic chemicals is more prevalent during deep-frying than during any other cooking method, such as grilling or roasting. For example, the content of total HCAs in deep-fried duck breast was significantly higher than that in grilled, pan-fried, and roasted samples (Omojola et al., 2015). The high concentration of these carcinogens in deep-fried foods could be caused by the high cooking temperature, as well as the use of oil during frying.

High-temperature treatment (above 150°C) facilitates the Maillard reaction in deep-fried foods (Bordin et al., 2013). Although the Maillard reaction develops desirable color and flavor in processed foods, it is also a crucial mechanism for AA and HCA formation. AA is generally formed at a temperature above 120°C by the reaction between asparagine and reducing sugars (Baskar & Aiswarya, 2018; Wu et al., 2022). The type of reducing sugar influences the formation of AA. Sansano et al. (2016) indicated that fructose could produce a higher amount of AA with asparagine at a lower temperature (125°C) than glucose (140°C). The presence of free amino acids other than asparagine, such as glutamine, alanine, glycine, and lysine, could reduce AA formation by promoting a competing reaction and/or covalently binding with AA (Rydberg et al., 2003).

HCAs are another type of undesirable product arising from Maillard reaction at temperatures of 150–250°C (Hosseini et al., 2016). Since creatine/creatinine, free amino acids, and reducing sugars are the three precursors of HCAs, HCAs are primarily present in protein-rich food products (Jägerstad & Skog, 2005). The presence of certain reducing sugars, such as dextrose, and amino acids, such as proline and tryptophan, could result in a reduction of HCA formation due to the blocked reaction between creatine and Maillard reaction intermediates. The mechanism of HCA formation and influencing factors have been extensively reviewed by Alaejos and Afonso (2011).

The hydrolysis, oxidation, and polymerization of oil are facilitated by the high temperature used during deep-frying, during which some precursors of PAHs are formed, such as cyclic compounds and free radicals (Choe & Min, 2007; Wang et al., 2022). For example, the pyrolysis of fat was considered the main mechanism of PAH formation in processed food (Alomirah et al., 2011). The PAHs of fried foods could be generated from fat contained within the food matrix, but the majority of PAH is derived from the pyrolysis of the cooking oil during frying. Lee et al. (2020) showed that the PAH concentration of deep-fried chicken (2.60–3.17 μg/kg) was significantly higher than that of air-fried chicken (1.96–2.71 μg/kg). The higher level of PAHs in deep-fried foods could be due to the high-temperature deterioration of frying oil resulting in PAHs' formation and those PAHs subsequently penetrating into the food. It is known that the aromatization and de-dehydrocyclization of monounsaturated hydrocarbons present in oil contribute to the PAH formation (Olatunji et al., 2014). The total PAH concentration in fried palm oil (4040 μg/kg) was more than 200 times higher than that in the fried fish (18.1 μg/kg) after 3–7 min frying at 150–180°C (Iwegbue et al., 2020). This indicates that frying oil provides a source of PAHs that penetrate into the food. In addition, frying oil acts as a carrier for PAH penetration into foods via oil uptake. Simko (2005) found a simultaneous decrease in fat and benzo[a]pyrene (a PAH) content in smoked sausages when the sausages were boiled and suggested that the benzo[a]pyrene diffused from the sausage into the water along with the fat. Thus, PAHs, due to their lipophilic nature, could be carried by penetrating oil (STO and PSO) into the foods during the frying process.

3 | APPLICATIONS OF CELLULOSE- AND CHITOSAN-BASED EDIBLE COATINGS IN DEEP-FRIED FOODS

3.1 | Applications in reduction of oil uptake and water loss

The application of edible coatings for reducing oil uptake and water loss in deep-fried products has been extensively investigated (Hashim et al., 2020; Kurek et al., 2021). For convenience, the term "edible coating" herein refers to both edible coatings and edible films, unless otherwise indicated. Although coatings and films can both be edible layers applied to food surfaces, their forms are quite different. Edible coatings are applied to the food surface as a liquid, usually by dipping or spraying, while edible films are applied as preformed solid sheets, on or between food components (Galus & Kadzińska, 2015). These layers, which act as barriers between the food and the frying oil, reduce the size and number of pores and change the hydrophobicity of the food surface, thus preventing water loss and oil uptake during the deep-frying process (Ananey-Obiri et al., 2018).

3.1.1 | Cellulose derivatives

Cellulose derivatives, such as MC, CMC, and HPMC, are commonly applied as coating materials in deep-fried foods to achieve oil uptake reduction. These materials could form a protective layer through reversible gelation. The gelation temperature of HPMC and MC is around 60°C and is inversely correlated to the concentration of cellulose and the degree of methyl substitution (Amboon et al., 2012; Thirumala et al., 2013). This thermally induced gel-forming property allows these modified cellulose materials to create a barrier for reducing water loss through the food surface during the immersion frying phase, offering a means to limit the oil penetration into the pores during the cooling phase (Amboon et al., 2012; Primo-Martín et al., 2010). Thus, applying such coatings before frying could give the food a crispy crust together with a moist core (Kurek et al., 2017).

The reduction in oil uptake of deep-fried food through applying cellulose derivatives in the coating of foods ranged from 6.3% to 95%, as shown in Table 1. The reported highest oil reduction using MC, CMC, and HPMC single coatings was 58% in cereal products (Albert & Mittal, 2002), 95% in chicken strips (Mona & Waleed, 2017), and 47% in French fries (Pahade & Sakhale, 2012), respectively. The performance of these coatings for oil uptake reduction depends on the formulation of the coating solutions, such as the type and concentration of cellulose and the addition of plasticizers (Table 1).

The efficiency in oil reduction and water retention of cellulose derivative coatings is affected by their constituted functional groups, such as the hydrophobic methyl and hydrophilic hydroxypropyl groups. Garcıá et al. (2002) explained that the relatively poor ability for oil uptake reduction and moisture retention with HPMC coatings compared to MC coatings was related to the presence of hydroxypropyl groups in the former, which may limit film-forming capacity through steric hindrance resulting in higher hydrophilicity of the coated food surface. Ayrancıét al. (1997) observed that the water vapor permeability of the HPMC and MC films was decreased with increasing molecular weight, which could be caused by the increased number of hydrophobic methyl groups. A similar observation was reported by Primo-Martín et al. (2010), who investigated the effects of different types and degrees of substitution on thermoregulation and oil and water barrier properties of MC, CMC, and HPMC coatings. They found that the coating made with K4M HPMC (Dow Chemical Company, Midland, MI, USA), which had the lowest degree of methyl substitution (22.5%) among the HPMCs, showed the highest oil reduction rate and lowest water retention rate in deep-fried snacks. Moreover, coating with F4M HPMC (Dow Chemical Company, Midland, MI, USA), with increased methoxyl (by 6.5%) and decreased hydroxypropyl group (by 0.9%) substitution compared to K4M HPMC, significantly increased water retention but had no influence on the reduction of oil uptake. This research indicated that the performance of cellulose-based coatings in oil reduction and water retention could be modified by using celluloses with different degrees of methyl and hydroxypropyl substitutions.

The oil barrier properties of the edible coatings could be further enhanced by using a higher concentration of cellulose, or by adding plasticizer or cross-linking agents (Table 1). A positive linear relationship between the concentration of cellulose and the level of oil uptake reduction has been found by many researchers (Garmakhany et al., 2008; Izadi et al., 2015). In terms of CMC, when the concentration increased from 1% to 3%, the oil content in fried cassava chips was reduced from 49.9% to 42.7% ($p < .05$) (Hashim et al., 2020). The reduced oil uptake associated with a higher concentration of coating was also observed by Ngatirah et al. (2022) in French fries coated with HPMC synthesized from empty fruit bunches and commercial CMC (1%–3%). The authors suggested that the higher concentration of cellulose (with a higher viscosity) contributed to better integrity of the coating structure, which would better cover the pores of the food surface preventing oil entry into the pores. However, the strengthened structure by coating with a higher concentration became too fragile and cracked, allowing the oil to leak into the food. This effect was also observed in a study of Chinese fried dough cake where 1% MC coating resulted in the highest oil reduction compared to 0.5% and 1.5% MC coatings (Han et al., 2021b). Similarly, Lua et al. (2020) reported that 1.0% MC coating resulted in the lowest oil uptake in potato strips compared with 0.5%, 1.5%, and 2% MC coatings, but the oil reduction with 2% MC coating was even lower than 0.5% MC coating. They indicated that the coating layer formed by 0.5% MC was too thin to cover the food surface evenly and hence did not prevent the oil penetration effectively. Alternatively, the higher concentration (2.0%) of coating solution formed a thicker layer but contributed to the development of cracks and larger pores on the coating surface subsequent to the frying process. The cracks and pores potentially act as channels allowing the suction of SO into the product during the cooling phase of frying. Despite the lower efficiency of the oil reduction due to the cracks, 35% and 40% oil reduction was achieved by 2.0% MC coating on fried potato strips and 1.5% MC coating in fried dough cake, respectively.

As a solution, the elasticity of the coating layer could be improved by adding plasticizers, such as sorbitol and glycerol (Table 1). The hydroxyl group of the plasticizers forms hydrogen bonds with coating biopolymers so that the flexibility of coating is improved. Better integrity of the MC coating was observed under the microscope after adding sorbitol (e.g., 0.5% sorbitol), which further contributes to higher oil reduction (Garcıá et al., 2002). Moreover, the addition of lipid plasticizers, such as glycerol, could

TABLE 1 Selected applications of cellulose-based edible coatings in deep-fried foods for oil uptake reduction

Materials	Concentration (%)	Food	Plasticizer	Reduction of oil uptake (%)	References
Methylcellulose (coating)	1	French fries	Sorbitol	15.53	Garcıá et al. (2002)
	0.5; 1; 1.5	Chinese fried dough cake		27–54	Han et al. (2021b)
	1	French fries		26.5–29.5	Pahade and Sakhale (2012)
	1	Potato strips		18–24	Zamani-Ghalehshahi and Farzaneh (2021)
	1	Dough systems	Sorbitol	30	Suárez et al. (2008)
	1	Potato chips	Sorbitol; glycerol	Up to 30	Tavera-Quiroz et al. (2012)
	1	Donuts		24.74	Zolfaghari et al. (2013)
(film)	2	Cereal product	Glycerol	58	Albert and Mittal (2002)
	0.5	Mushroom		10–22	Martínez-Pineda et al. (2021)
Carboxymethylcellulose (coating)	0.5; 1	Potato chips		38.73–57.03	Garmakhany et al. (2008)
	1; 2; 3	Cassava chips		5–10	Hashim et al. (2020)
	1.5	Chicken strips	Glycerol	87–95	Mona and Waleed (2017)
	1	Potato strips		36–54	Rimac-Brnčić et al. (2004)
	0.5; 1; 1.5	Shrimps		14–34	Izadi et al. (2015)
	2	Eggplant rings		75	Eissa et al. (2013)
	1; 2; 3	French fries		9–19	Ngatirah et al. (2022)
(film)	2; 6; 10; 14	Potato pellet	Glycerol	Up to 50	Angor (2016)
Hydroxypropyl methylcellulose (coating)	1	Chicken nuggets		54	Altunakar et al. (2006)
	2	French fries	Sorbitol	6.3–7.6	Garcıá et al. (2002)
	1	French fries		37.8–46.9	Pahade and Sakhale (2012)
	1; 2; 3	French fries		3–15	Ngatirah et al. (2022)

also modify the hydrophobicity of coatings to enhance water barrier properties (Sothornvit & Krochta, 2005). The moisture content of MC-coated deep-fried potato chips was significantly increased as the result of plasticization with glycerol (0.5%, w/v) (Tavera-Quiroz et al., 2012).

Interestingly, the study of Martínez-Pineda et al. (2021) showed that the performance of 0.5% MC edible coating on oil reduction was enhanced with increased coating solution temperature. Coating with MC solution at 40°C showed the lowest oil content ($p < .05$) in deep-fried mushroom stem and cap (15% and 20%, respectively), compared to coating at 15 and 30°C. Although the effect of coating solution temperature on reducing oil content was not addressed, it could be related to the onset gelation of MC at 40°C where the viscosity of the coating solution showed a sharp increase. As described above, the water escapes from the inside of food during frying, which may challenge the coating gel forming an integral layer, although the time of gelation is short. Compared to other coatings, the MC coating solution at 40°C had an earlier gelation that promotes the formation of a smoother crust layer when immersed in hot oil (Lua et al., 2020). However, this interesting effect of coating solution temperature on increased oil reduction rate requires further investigation, in elucidating the mechanism.

3.1.2 | Chitosan

Chitin is a natural biopolymer and is a component in the shell of crustaceans and the cell wall of fungi. Chitosan is derived from chitin by deacetylation of chitin under alkaline conditions and consists mainly of poly-β-(1-4)-2-acetamido-D-glucose dependent on the degree of deacetylation of the chitosan product. Chitosan can be used to form a continuous coating layer on foods (Hassan et al., 2018). Since chitosan has very low solubility in water but is soluble in acidic solutions due to protonation of the amino group that transforms it into a hydrophilic entity, an acid (such as acetic acid) is usually added as an acidic modifier in making chitosan coating solutions. Thus, the acidic chitosan coating sometimes could result in a decreased pH in the coated foods, such as fresh-cut potatoes (Kurek et al., 2021). Chitosan coatings are suitable gas barriers but have low water resistance. They are widely applied to fresh foods such as fruits to reduce transpiration rate and control microbial growth (Hassan et al., 2018). Though chitosan was less used for oil reduction in deep-fried foods compared with cellulose derivates, studies have shown that using chitosan alone or as an additive to flour batter can significantly reduce oil uptake in deep-fried foods (Table 2).

TABLE 2 Selected applications of chitosan in deep-fried foods for oil uptake reduction

Coating type	Concentration (%)	Foods	Reduction of oil uptake (%)	References
Chitosan only coating	0.5; 1; 1.5	Eggplant	6.9–32.7	Nasirvand and Javadi (2018)
	2	Eggplant rings	49	Eissa et al. (2013)
	0.6	French fries	21.5	Al-Asmar et al. (2018)
	2	French fries	8.28	Kizito et al. (2017)
In batter system	0.5; 1; 1.5; 2	Fish sticks	36.84–80	Martin Xavier et al. (2017)
	0.5; 1.5	Crust of Kurdish cheese nuggets	10–35	Ansarifar et al. (2012)
	0.5; 1.5	Kurdish cheese nuggets	3–19	Ansarifar et al. (2015)

The coatings made from chitosan have been shown to reduce the oil content of French fries by up to 21.5% (Al-Asmar et al., 2018; Kizito et al., 2017). Another study using a 2% chitosan coating solution for eggplant rings resulted in a smoother surface after deep-frying and a 49% oil uptake reduction compared with the uncoated samples (Eissa et al., 2013). Similar to cellulose-based coatings, the efficiency of oil reduction using chitosan coatings is also affected by the concentration of the chitosan. For example, the oil uptake of eggplant samples coated with 0.5%, 1%, and 1.5% of chitosan (containing sorbitol as the plasticizer) was reduced by 6.9%, 13.2%, and 32.7%, respectively (Nasirvand & Javadi, 2018), suggesting a higher chitosan concentration favors to a higher reduction of oil uptake.

The addition of chitosan enhanced the oil-reducing effect of a flour-based batter. It resulted in 37%–80%, 3%–19%, and 10%–35% oil reduction in deep-fried fish sticks (Martin Xavier et al., 2017), Kurdish cheese nuggets (Ansarifar et al., 2015), and the crust of Kurdish cheese nuggets (Ansarifar et al., 2012), respectively. These studies on chitosan-based batter coatings also indicated that the concentration of chitosan is positively correlated with the oil-reducing efficiency of the batter, a result also seen with chitosan coating alone (Nasirvand & Javadi, 2018). Based on the reported research findings, the effect of chitosan concentration on improving the efficiency of oil reduction seems to be more consistent compared to cellulose.

There is, however, no certainty that a higher concentration of chitosan coating will always produce a greater oil reduction in deep-fried foods. As discussed above, the lowest oil uptake resulted from the cellulose coating that was able to form an even layer on the food surface, without the generation of cracks during frying. Thus, the surface properties of foods (e.g., porosity and pore size) should also be considered in the coating formulation, to assure the coating solution with a certain concentration (viscosity) can adhere tightly to foods and fill the pores on the food surface. Although the efficiency of cellulose and chitosan coating on oil reduction of fried foods varies, cellulose and chitosan coatings are both promising materials for the coatings-based strategy for the reduction of oil uptake in deep-fried foods.

3.2 | Applications in reduction of AA

Cellulose- and chitosan-based edible coatings were recently found to inhibit AA formation in deep-fried products (Table 3). Han et al. (2021a) found that the AA content of the Chinese dough cake fried at 180°C for 2 min was reduced from 117.55 to 81.28 μg/kg after coating with 1% MC. They suggested that the coating material acts as a gel layer, modifying the surface, and interferes with

TABLE 3 Selected applications of cellulose- and chitosan-based edible coatings in deep-fried foods for reduction of acrylamide

Materials	Concentration (%)	Food	Reduction of acrylamide (%)	References
Methylcellulose (coating)	1	Chinese fried dough cake	37.4	Han et al. (2021a)
	0.5; 1; 1.5	Chinese fried dough cake	14–37.3	Han et al. (2021b)
	0.5; 1; 1.5; 2	Fried potato	Up to 82	Lua et al. (2022)
Carboxymethylcellulose (coating)	0.3; 0.7	Potato slices	60.6 and 62.9, respectively	Sadat Mousavian et al. (2015)
Chitosan (coating)	0.6	French fries	38	Al-Asmar et al. (2018)
	1	Potato chip	40.9	Champrasert et al. (2021)
(In batter system)	0.27; 0.54	Fried batters	Up to 59	Sansano et al. (2016)
	0.54	Fried batters	32–69	Sansano et al. (2017)

molecular interactions between asparagine and reducing sugars, which are the precursors for the formation of AAs in the Maillard reaction. In another study by Han et al. (2021b), the concentration of MC coating influenced its function in reducing AA formation in fried Chinese dough cake. The AA concentration was reduced from 101.07 to 73.7 μg/kg, with the MC concentration increasing from 0.5% to 1.5%. The negative relationship between the concentration of AA and coating material was also observed in fried potato slices by Sadat Mousavian et al. (2015). They found that the 0.7% CMC coating resulted in a higher reduction of AAs (62.9%) compared to the 0.3% CMC (60.6% reduction) in potato slices fried at 170°C for 6 min. Interestingly, applying ultrasonic-treated MC batter (at 48 kHz, 20 W, and 25°C for 20 min) on fried potatoes resulted in a doubling of the efficiency of AA reduction compared to nontreated MC batter (Lua et al., 2022). The input of sonication energy resulted in a loose backbone structure of MC facilitating MC absorbing amine groups during deep-frying.

Chitosan coating was applied to French fries (Al-Asmar et al., 2018) and potato chips (Champrasert et al., 2021), resulting in a 38% and 40.9% reduction of AA, respectively. Sansano et al. (2016) investigated the effect of chitosan on the asparagine-reducing sugars (glucose, fructose, or mixture) model system. They observed that the amino group of chitosan could compete with free amino groups of asparagine to bind to the carbonyl group of reducing sugars, leading to the reduction in AA formation. Thus, the inhibitory effect of chitosan on AA formation depends on the concentration of chitosan in relation to the content of amino groups. It was observed that a 0.54% chitosan addition resulted in a 31.6% reduction of AA in the batter system when fried at 180°C for 7 min, compared to a 25.7% reduction with 0.27% chitosan (Sansano et al., 2016). A higher reduction of AA could also be achieved using chitosan with a lower molecular weight (Chang et al., 2016) or a higher deacetylation degree (Sansano et al., 2017). For example, the concentration of AA in fried batter was reduced by 45% when using the low-molecular-weight chitosan (50–190 kDa) compared to a 15% reduction of AA by high-molecular-weight chitosan (310—375 kDa) (Chang et al., 2016). This effect could be caused by the larger number of free amines from the low-molecular-weight chitosan competing with free asparagine that could mitigate the formation of AAs.

Water plays an important role in the rate of the Maillard reaction. The reaction rate increases until the water activity reaches a certain level where the reactants have the highest solubility and mobility, then the reaction rate decreases due to the diluted reactants by the excessive water (Wong et al., 2015). Since cellulose and chitosan coatings also contribute to moisture retention of foods during deep-frying, the increased water content on the food surface may affect the function of coating on AA reduction. This may explain why the inhibition rate of AAs was not doubled while the concentration of cellulose or chitosan coating was doubled in the above studies (Sadat Mousavian et al., 2015; Sansano et al., 2016). Thus, the efficiency of cellulose and chitosan edible coating on AA reduction could depend on both the coating concentration (the number of competing groups) and the water retention capacity of the coating (water content of food) during deep-frying. Building an understanding of these relationships will enable the prediction and control of AA formation and hence warrants further investigation.

3.3 | Effects of coatings on sensory attributes of deep-fried foods

Applying cellulose- or chitosan-based edible coatings influences the hardness and color parameters of deep-fried food products. Altunakar et al. (2006) reported a softer texture in HPMC-coated chicken nuggets based on the decreased hardness measured using a texture analyzer. Due to the increased water content as a result of an edible coating, the reduced hardness was also observed in Chinese fried dough cake coated with MC (Han et al., 2021a) and fried fish sticks coated with chitosan (Martin Xavier et al., 2017). Because of the reduced Maillard reaction, a lower b^* value (yellowness) was observed in the coated fried foods, such as Chinese fried dough cake and doughnut coated with MC, as well as fried potato strips coated with CMC or chitosan (Han et al., 2021a; Kizito et al., 2017; Zolfaghari et al., 2013). The inhibitory effect of chitosan on nonenzymatic browning was also observed in fried eggplant rings (Ali et al., 2011). As discussed above, the free amino groups in chitosan facilitate the inhibition of the Maillard reaction and therefore explain the lighter brown color on the surface.

Acetic acid is sometimes used to dissolve chitosan but this results in an acidic chitosan coating, which was found to increase the acidity of the fried eggplant (Nasirvand & Javadi, 2018). Nevertheless, this increased acidity did not cause significant changes in the taste or overall acceptability of the eggplant. However, as the research on this aspect is limited, it is difficult to draw conclusions regarding the effect of acidic chitosan coatings on the pH or sensory quality of cooked foods, including deep-fried products. On the other hand, the impact of acidic chitosan coating on the acidity or pH of fresh foods is inconsistent. For example, the application of chitosan coating, dissolved using 1% acetic acid, caused a decreased pH in fresh-cut potatoes (Kurek et al., 2021), but it did not cause a significant change in the pH in raw salmon fillet (Xiong et al., 2021). These different results on pH changes may be attributed to the different surface properties of foods that result in different pickup rates of acidic coatings. Since the pH and acidity of foods are critical to food quality and consumer acceptability, the effect of acidic chitosan coating on the pH and taste of fried foods warrants further investigation. Alternatively, modifying food pH by using a food-compatible alkali such as sodium bicarbonate prior to coating could be a potential solution (Fang et al., 2018).

Generally, there are no reported adverse effects of cellulose- and chitosan-based coatings on sensory attributes (i.e., color, taste, aroma, and overall acceptability) of coated deep-fried products, such as potato chips, French fries, or eggplants (Garmakhany et al., 2008; Nasirvand & Javadi, 2018; Pahade & Sakhale, 2012; Zamani-Ghalehshahi & Farzaneh, 2021). In fact, where coatings were applied, improvements in crispness and texture were widely reported in deep-fried foods, such as CMC-coated potato pellet chips, chicken strips, and cassava chips (Angor, 2016; Hashim et al., 2020; Mona & Waleed, 2017). Edible coatings can form a crust on the food surface and reduce water loss. A crispy surface with a juicy interior is a highly desirable attribute of deep-fried foods for consumers (Soto-Jover et al., 2016). These findings suggest that cellulose- and chitosan-based coatings could help increase consumer acceptability of deep-fried foods.

3.4 | Advantages of cellulose- and chitosan-based coating in deep-fried foods

Although reduction of oil uptake could be achieved by coatings from proteins (e.g., SPI) and other polysaccharide materials (e.g., pectin), cellulose- and chitosan-based coatings have greater advantages. Although cellulose- or chitosan-based coatings resulted in lower moisture retention in deep-fried foods than protein-based coatings due to their hydrophilic nature, excessive reduction in moisture loss may result in a soggy texture (Albert & Mittal, 2002; Asokapandian et al., 2020; Klangmuang & Sothornvit, 2018). The lower moisture barrier property of cellulose- or chitosan-based coatings may help the coated products to remain crisp after the frying process, as a consequence of greater water loss. Thus, cellulose- and chitosan-based coatings could be more suitable for reducing the oil uptake in deep-fried foods, especially for a crisp texture experience in products such as chips.

With regard to food safety, cellulose and chitosan are the two most common materials used to reduce AA levels. In comparison, protein-based coatings, such as SPI, have a lower inhibitory effect on the formation of AA, because protein material provides an asparagine amino group for the Maillard reaction (Han et al., 2021b). In addition, cellulose and chitosan have the added advantage of reducing the content of HCAs and PAHs in processed foods (Kim, Han, et al., 2021; Zhang et al., 2021), which will be discussed in the following sections. Thus, cellulose- and chitosan-based coatings have great potential to reduce chemical hazards such as HCAs and PAHs in deep-fried foods. In addition, unlike soy and whey proteins, there are no allergy concerns in the application of cellulose- and chitosan-based coatings. Furthermore, cellulose and chitosan are dietary fibers that are known to be beneficial for human health. For example, MC has been used in the treatment of constipation and chitosan can help reduce cholesterol (Hillier, 2007; Sansano et al., 2016).

Commercially, it is economically viable to use cellulose and chitosan as the coating materials. Cellulose and chitosan are the first and second most abundant natural biopolymers, which are obtained from plants and as the byproduct of seafood processing, respectively (Bedade et al., 2019). They are commercially available at low cost (Ho & Leo, 2021; Lua et al., 2020). In addition, because of the high viscosity of polysaccharides, only a small amount of native or modified cellulose or chitosan (commonly, 1%–2%) is needed to form coatings or films, minimizing the adverse effects on the appearance of the food. For example, CMC edible coatings (0.5%, w/w) and films (2%, w/v) were reported to have good oil barrier properties for French fries and potato pellet chips, respectively, without any significant changes in sensory attributes including color (Angor, 2016; Daraei Garmakhany et al., 2014). In contrast, protein-based edible coatings are usually made with a higher concentration of 3%–10% protein (Ananey-Obiri et al., 2018), which may involve extra costs for the industry or cause a negative consumer sensory experience of coated products. For example, huge bubbles formed on the surface of gluten (12.5%)-coated cereal products during frying, while 2% of MC coating resulted in a shiny surface with good color (Albert & Mittal, 2002).

4 | POTENTIAL OF CELLULOSE- AND CHITOSAN-BASED EDIBLE COATINGS FOR HCA AND PAH REDUCTION IN DEEP-FRIED FOODS

4.1 | HCA reduction

Cellulose and chitosan, in the form of edible coating or additives, are reported to inhibit HCA formation in processed foods. For instance, with the addition of 1% MC powder, the HCA content of a fried beef burger (200°C, 5 min) was reduced from 60.1 to 14.7 ng/g (Persson et al., 2004). The application of 1% chitosan coating resulted in a 24.58% and 68.09% reduction of total HCAs in deep-fried (at 190°C) and barbecued (at 190°C) fish fillet, respectively (Mirsadeghi et al., 2019). The mechanism of cellulose and chitosan materials for inhibiting HCA formation has been proposed by Zhang et al. (2021). Carboxyl groups in modified cellulose could interfere with the decarboxylation process, which is an essential step in HCA formation in the Maillard reaction, and the amino groups in chitosan could react with reactive carbonyl compounds that are key intermediates in HCA formation.

The inhibitory activity of cellulose and chitosan on HCA formation is also related to their concentration. Decreased levels of HCA in beef patties grilled at 220°C for 160 s were found with the increasing addition of CMC from 1% to 3% (Gibis & Weiss, 2017). The effect of the concentration of added chitosan (0.5%, 0.75%, and 1%) on the HCAs content in cooked meatballs at different temperatures (150, 200, and 250°C) was investigated (Oz et al., 2017). The reduction of HCAs by chitosan also showed a positive relationship with the increased concentration of chitosan and temperature; up to 59.8% of HCAs were reduced at 250°C with 1% chitosan added. Moreover, the effect of chitosan molecular weight (50–190 and 190–310 kDa) on HCA formation were investigated in beef chops cooked at different temperature (150, 200, and 250°C) and with various levels of chitosan (0.25%–1%) (Oz et al., 2016). Overall, chitosan with medium molecular weight (190–310 kDa) had a better inhibition rate at all three temperatures. However, the authors considered that the results were difficult to compare due to the high number of variables, for example, the types of HCAs analyzed, meat size, and cooking conditions.

As discussed earlier, the Maillard reaction is affected by the water activity of foods. Gibis and Weiss (2017) observed a 20% reduction of HCAs in grilled beef patties by adding 10% water that contributed to the dilution of the precursors of the Maillard reaction. However, their results showed that the effect of the addition of water on the reduction of HCAs is not comparable to the addition of CMC (1%–3%), where the latter resulted in significantly higher moisture retention in grilled beef patties ($p < .05$). Thus, further studies on the association of HCA-reducing efficiency and water-retaining capacity of cellulose and chitosan coatings on deep-fried foods are required to clarify this effect.

Chitosan-based materials also have great potential to reduce dietary HCAs by adsorption (Zhang et al., 2021). Arimoto-Kobayashi et al. (1997) compared the adsorption capacity of chitosan and chlorophyllin–chitosan complex to nine types of HCAs in Na phosphate–KCl buffer (pH 7), in which the latter had a higher adsorption rate to all nine HCAs. For example, for 3-amino-1-methyl-5H-pyrido[4,3-b]indole (Trp-P-2, a three-ring HCA), the adsorption rate with chitosan and chlorophyllin–chitosan complex was 11% and 99%, respectively. Furthermore, an in vivo study by Sugiyama et al. (2002) showed that with the addition of chlorophyllin–chitosan complex, the DNA adduct formed from Trp-P-2 in the liver and lungs of CDF_1 mice was significantly decreased. Although the application of chitosan to adsorb HCAs in food systems is limited, these studies indicated that chitosan-based materials could potentially reduce the bioaccessibility of HCAs by binding to them. MC, on the other hand, does not bind to HCAs including Trp-P-2 in water solutions at 20 mg/ml (Persson et al., 2004).

The above studies imply that there is value in using cellulose and, especially, chitosan as edible coating materials to reduce HCAs in deep-fried foods. Compared to when these coatings are used as a powder and mixed with food ingredients in constructed foods, such as meatballs, the use of cellulose and chitosan as a coating on the food surface likely causes a different result in HCA reduction. Considering the positive health implications of reduced HCA consumption, more studies should be performed investigating the application of cellulose- and chitosan-based edible coatings for HCA reduction in deep-fried foods.

4.2 | PAH reduction

Cellulose- and chitosan-based materials have been shown to adsorb PAHs in aqueous systems (Björklund & Li, 2018; Crisafully et al., 2008; Naing et al., 2016). PAHs could be adsorbed onto chitosan via hydrogen bonding and hydrophobic interactions as they are nonpolar compounds (Zango et al., 2020). Similarly, cellulose adsorbs PAHs via weakened hydrogen bonds (Wang et al., 2007). Therefore, due to the increased number of aromatic rings and hydrophobicity, the PAHs with higher molecular weight could be more easily adsorbed onto cellulose and chitosan. This characteristic of adsorption facilitates the removal of PAHs from deep-fried foods since the level of high-molecular-weight PAH species dominates in deep-fried products and is also more harmful and toxic to humans (Gao et al., 2016; Iwegbue et al., 2020). By installing the cellulose aerogels above the smoke regulator in the smoking chamber, Kim, Han, et al. (2021) observed up to a 24% reduction in total PAHs' levels in the smoked pork sausages. Kim, Kim, et al. (2021) applied a similar cellulosic aerogel as a filter for oil extraction from roasted sesame seeds, and the PAH levels in oil were reduced from 2.97 to 1 μg/kg. The adsorbing capacity of cellulosic aerogel for PAHs was positively associated with the ratio between aerogels and oil volume (w/w). More importantly, there was no significant change in the quality parameters of the oil, such as fatty acid composition, acid value, peroxide value, and chromaticity. These two studies also indicated that the binding stability of cellulose to PAHs is stable in oil, a nonpolar solution. Based on the adsorption ability of PAHs, cellulose and chitosan could potentially be used as edible coatings to reduce PAH levels in processed foods (Wang et al., 2022). These coatings may bind with PAHs that remain on the food surface, such as the PAHs carried by surface oil.

Although the potential of cellulose- and chitosan-based edible coatings for PAHs' reduction has exciting implications, more evidence of the binding stability of the bound PAHs on cellulose and chitosan is needed, including in different heating systems used during cooking. Moreover, since the coating-bound PAHs are eaten together with the foods, the health implication of PAHs possibly released during digestion (gastric and small intestinal) or colonic fermentation should be considered prior to application. Boki et al. (2007) found that CMC could firmly bind with PAHs in artificial gastric juice and intestinal juice, while the bioaccessibility of PAH bound by other celluloses and chitosan needs to be further investigated. One solution to bypass this health issue is to employ easy-to-peel cellulose- and chitosan-based edible coatings, similar to peelable sausage casings, thus avoiding consuming the coating-bound PAHs.

As oil is known to be the carrier of PAHs in deep-fried foods, edible coatings have great potential for PAH reduction by reducing the penetration of PAHs with oil (STO and PSO) uptake into foods. While the potential function of edible coatings for reducing PAHs in deep-fried foods has not been studied, it has been shown that PAH penetration into the product during the smoking of sausages could be inhibited by an edible barrier layer, such as sausage casings (García-Falcón & Simal-Gándara, 2005). The smoother surface and lower porosity of the casings could help reduce the penetration of PAHs into the sausage during the smoking process (García-Falcón & Simal-Gándara, 2005; Gomes et al., 2013; Ledesma et al., 2015). In comparison to casings, edible coatings modify the porosity and hydrophilicity of food surfaces and hence reduce the penetration of oil in deep-fried foods (Kurek et al., 2021).

Moreover, cellulose- and chitosan-based edible coatings could be used as a carrier of antioxidants, to reduce PAH levels in deep-fried foods. Antioxidants, such as tert-butylhydroquinone, could inhibit the PAHs' formation formed via oxidizing radicals in peanuts during deep-frying (Zhao et al., 2017). However, the inhibitory effect of antioxidants on PAH formation could be reduced as a result of their self-oxidation during storage (Wang et al., 2022). Cellulose- and chitosan-based edible coatings could effectively protect the antioxidant from oxidation during storage (Ponce et al., 2008; Razavi, 2016). Thus, applying cellulose- and chitosan-based edible coatings with the incorporation of antioxidants may enhance their function for PAH reduction in deep-fried foods.

5 | POTENTIAL AND HEALTH IMPACTS OF CELLULOSE-/CHITOSAN-BASED NANOCOMPOSITE COATINGS

The applications and health impacts of edible coatings with novel nanoformulation are hot research areas from the last decade (Osheba et al., 2013; Shen et al., 2022). They are composite coatings consisting of a matrix of traditional coating materials (i.e., cellulose and chitosan) with nanoparticles to reinforce coating strength (Sharma et al., 2020). These nanoparticles can be inorganic compounds, such as TiO_2, or organic nanoparticulate polymers, such as cellulose and chitosan. The synthesis of cellulose and chitosan nanoparticles and the application of cellulose-/chitosan-based nanocomposite coatings have been well reviewed recently (Jampílek & Kráľová, 2021; Pirozzi et al., 2021).

5.1 | Potentials of nanoformulation on the performance of edible coatings

Reports on the application of cellulose/chitosan nanoparticles in chitosan-/cellulose-based coatings are noted (Table 4). Since both cellulose and chitosan have a large number of hydroxyl groups due to the sugar structure, the hydrogen bonds and electrostatic interactions between the nanoparticles and coating matrix result in a strong network and smaller pores (Pirozzi et al., 2021). Thus, cellulose- and chitosan-based nanocomposite coatings showed better mechanical properties (e.g., tensile strength), thermal stability, gas and water barrier properties, and antimicrobial activity (Ghosh et al., 2021; Lorevice et al., 2014; Salari et al., 2018). Salari et al. (2018) observed a decrease ($p < .05$) in water solubility, water vapor permeability, and water contact angle of chitosan film by the incorporation of cellulose nanocrystals (2%–6%). They concluded that the interaction between the film matrix and the nanocrystals reduced the hydrophilic groups and increased the cohesiveness on the food surface, resulting in increased surface hydrophobicity. The study of de Moura et al. (2009) showed that the size of chitosan nanoparticles was a key factor in the water vapor permeability and elongation of nanocomposite HPMC film. The addition of very small chitosan nanoparticles (85 nm) resulted in the lowest water vapor permeability and highest elongation ($p < .05$) of HPMC film compared to the larger chitosan nanoparticles (110 and 221 nm). The authors indicated that the chitosan nanoparticles with smaller particle sizes have more ability to fill up the empty spaces of the

TABLE 4 Selected applications of cellulose/chitosan nanoparticles in chitosan-/cellulose-based coatings

Nanoparticles	Coating materials	Foods	Fundings	References
Cellulose nanofiber	Chitosan coating	Kiwifruits	Composite coating was effective in reducing weight loss, firmness loss, respiration rate, and microbial count and maintaining saturation of color, without remarkable change in pH.	Ghosh et al. (2021)
Bacterial cellulose nanocrystal	Chitosan film	No	Addition of nanoparticles improved the physical and mechanical properties, thermal stability (glass transition and melting temperature), and antimicrobial properties of chitosan film.	Salari et al. (2018)
Chitosan nanoparticles	CMC film	Pork	Addition of chitosan nanoparticles reduced weight loss and inhibited protein degradation and lipid oxidation of pork at $4 \pm 1°C$ for 15 days.	Shen et al. (2022)
Chitosan nanoparticles	HPMC film	No	Chitosan nanoparticles increased the tensile strength, glass transition, temperature, and water barrier property of HPMC film.	Lorevice et al. (2014)
Chitosan nanoparticles	HPMC film	No	Tensile strength, water barrier property, and thermal degradation temperature were increased by the addition of chitosan nanoparticles. The improvement in the tensile strength and water resistance was associated with the decreased size of chitosan nanoparticles.	de Moura et al. (2009)

Abbreviations: CMC, carboxymethylcellulose; HPMC, hydroxypropyl methylcellulose.

porous film matrix; hence, their addition is more beneficial for water resistance and tensile strength of HPMC film. Since the oil uptake is positively associated with the porosity of food surface and moisture loss during deep-frying (Ziaiifar et al., 2010), the nanocomposite edible coating containing a smaller nanoparticle size could contribute to a lower oil uptake in fried foods. Although the applications of cellulose-/chitosan-based nanocomposite coatings now mainly focus on the preservation of raw foods (e.g., pork and kiwifruits), such coatings improved food quality and safety by inhibiting weight loss (water resistance), protein degradation, and lipid oxidation during storage (Ghosh et al., 2021; Shen et al., 2022).

Compared to cellulose nanoparticles, chitosan nanoparticles have been applied as a coating or added into other coating matrices, such as grass pea flour and pectin, to reduce oil uptake and water loss of deep-fried fish finger (Osheba et al., 2013) and Kobbah (Al-Asmar et al., 2020). In these studies, chitosan nanoparticles were prepared with food-grade sodium tripolyphosphate via ionic gelation. By applying 4% chitosan nanoparticles as the coating matrix, the deep-fried fingers had a fat and moisture content of 4.56% and 52.70%, respectively, relative to 11.95% and 49.78% for the samples coated with chitosan solution only. The addition of chitosan nanoparticles into grass pea flour or pectin used to coat the Kobbah also resulted in an increase in water content and a reduction of oil content after deep-fry (Al-Asmar et al., 2020). This can be explained by the fact that tripolyphosphate-crosslinked chitosan nanoparticles formed a more compact and denser coating layer than the chitosan coating, which helped to inhibit oil and water transfer. Moreover, no significant change in pH was found in homogenized fish fingers coated by acidic chitosan nanoparticles (Osheba et al., 2013), contrasting with decreased pH in fresh-cut potatoes described above (Kurek et al., 2021).

The above study indicated that cellulose/chitosan nanocomposite coatings could improve the oil-reduction efficiency in deep-fried foods and hence reduce PAH penetration into foods. The nanoparticles have smaller particle sizes but larger surface areas, which could enhance the inhibitory reaction to reduce AA and HCA formation during deep-frying. These coatings also showed notable water and gas barrier properties and antimicrobial activity that would prevent spoilage and nutritional loss of foods during storage and reduce the health risk in food consumption for consumers.

5.2 | Health concerns of cellulose-/chitosan-based nanocomposite coatings

Although cellulose and chitosan are common food additives without toxicity, the concept of designing and including nanoparticles in food coatings may raise concerns about the risks of health effects. The occurrence of organic nanoparticles in foods and human digestion is prevalent, such as nanostructures of casein micelles from native milk (Ogura & Okada, 2017). These organic nanoparticles, including cellulose and chitosan nanoparticles, were considered less toxic than inorganic nanoparticles due to their low biopersistence (McClements & Xiao, 2017; Onyeaka et al., 2022). In fact, most toxicity has been reported for inorganic nanoparticles, such as TiO_2 and Fe_2O_3 nanoparticles, as they could penetrate into microbial cells and generate reactive oxygen species thereby damaging key cellular components, such as DNA (McClements & Xiao, 2017; Ranjan et al., 2019).

The study of De Lima et al. (2010) indicated that the toxicity of chitosan nanoparticles was dependent on particle size and concentration. They investigated the genotoxicity and cytotoxicity of chitosan nanoparticles with three particle sizes (60, 82, and 111 nm) and concentrations (1.8, 18, and 180 mg/ml), and found that chitosan nanoparticles were toxic to cells (decreased mitotic index values) only when the size is larger than 82 nm at a higher concentration (180 mg/ml), though they did not cause any damages on DNA. The authors also indicated that the cellular uptake mechanism of nanoparticles varied with their particle size, which further influences their interaction with organelles and macromolecules. On the contrary, most studies revealed that cellulose and chitosan nanoparticles were nontoxic to humans (Bugnicourt & Ladavière, 2016; Rampino et al., 2013; Yu et al., 2019). Some studies indicated that nanocellulose or chitosan nanoparticles could benefit human health through the interference of intestinal digestion (DeLoid et al., 2018; Dube et al., 2010). For example, chitosan nanoparticles prepared with sodium tripolyphosphate were found to enhance the intestinal sorption of antioxidants (catechins and epigallocatechin gallate) in mice (Dube et al., 2010).

With respect to the contradictory results of published studies on the toxicity of cellulose and chitosan nanoparticles, their safety is still not clear. According to the guidelines published by EFSA (2011) on the risk assessment of the application of nanoscience and nanotechnologies in the food and feed chain, the uncertainties of nanomaterials should be fully addressed by the risk assessment before application. Even if cellulose/chitosan nanocomposite coatings have great potential to improve the food quality and safety of deep-fried foods, further studies on their toxicity are needed, such as the breakdown and fate of cellulose and chitosan nanoparticles during passage through the human digestive tract at meaningful concentrations.

6 | CONCLUSION AND FURTHER PERSPECTIVES

The high oil content and the presence of carcinogenic AAs, HCAs, and PAHs in deep-fried foods are critical for consumer health and hence for the food industry. As the most common types of edible coatings for oil reduction, cellulose- and chitosan-based coatings have a minimal negative impact on sensory attributes and positive advantages for the product including remaining crispiness, low cost of application, no allergy concerns, and positive health implications. The functional groups of cellulose and chitosan materials could react with the precursors of AAs and HCAs and inhibit their formation during the deep-frying process. Based on the inhibitory effects of edible coatings on oil uptake and the adsorption ability of PAHs, cellulose- and chitosan-based edible coatings could be a potential strategy to reduce PAHs' levels in deep-fried foods.

Because of these potential functions and advantages of cellulose and chitosan coatings, their applications are expected to have a high impact on industrial processing. The biggest challenge for the commercialization of such coatings in food industries could be the acceptance of consumers, especially to safety and sensory attributes. Although the concept of edible coating has been developed over the past decades, the most common experience of consumers with edible coatings could be still an expectation that it is fruit wax. Thus, customer awareness of perceived benefits, food safety, and quality of cellulose-/chitosan-coated fried foods is critical. Negative impacts of the coatings on sensory attributes, including taste changes due to the decreased pH in chitosan-coated foods, need to be avoided. Overall, cellulose- and chitosan-based edible coatings have great potential to deliver healthier and safer deep-fried food products for consumers.

The emergent use of cellulose and chitosan nanoparticles within edible coatings that are engineered to improve physical properties (i.e., water resistance and molecular spreading) and mechanical properties (i.e., tensile strength) offers opportunities for the development of healthier food products. These nanoformulated cellulose- and chitosan-based coatings promise to reduce oil uptake during deep-frying and may further reduce the level of AAs, HCAs, and PAHs in deep-fried foods. The somewhat uncertain safety profiles of the nanoparticles, however, might limit their full potential in foods, and further investigations on their absorption, biotransformation, and toxicity upon ingestion are needed.

AUTHOR CONTRIBUTIONS

Zun Wang conceptualized the idea of the study, designed the methodology, curated the data, performed investigation, validation, and visualization, conducted formal analysis, wrote the original draft, reviewed and edited the manuscript, and provided software. Ken Ng, Robyn Dorothy Warner, and Regine Stockmann performed supervision and reviewed and edited the manuscript. Zhongxiang Fang conceptualized the idea of the study, performed supervision, provided resources, administered the project, reviewed and edited the manuscript, acquired funding, and designed the methodology.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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